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MODEL STUDIES OF EXPLOSIVE STORAGE CUBICLES

by

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CONTENTS

ABSTRACT

Experimental results are presented on the magnitude and distribution of the pressure-time blast loading resulting from internal blasts on the walls of partially vented enclosures. Experiments were conducted using 1/6 scale steel models of typical storage cubicles subjected to the internal detonation of spherical bare pentolite charges. The principal variables were: the charge size, its location within the enclosed space, and the shape of the enclosed space.

FOREWORD

This work was conducted under BUWEPS Task No. RUME-3-E-000/210-1/F008-10-004 to study the blast loading on dividing walls, resulting from internal explosions, with a view to providing the blast loading information required for specifying design criteria for explosive storage and manufacturing facilities.

This report is based on a series of tests conducted by F. D. Altman, W. Graham and C. F. Johnson of the Warhead and Terminal Ballistics Laboratory.

Acknowledgement is given to K. Abt and G. W. Gemmill of the Computation and Analysis Laboratory for their suggestions in test planning, and the statistical interpretation of the test data.

This report has been reviewed by the following personnel of the Warhead and Terminal Ballistics Laboratory:

J. C. TALLEY, Head, Research Division
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APPROVED FOR RELEASE:

/s/ RALPH A. NIEMANN
Acting
Technical Director

INTRODUCTION

This is a report of an experimental investigation to determine the magnitude and distribution of loads resulting from internal blast on the walls of a partially vented enclosure. The effects of air blast in free air and in completely enclosed spaces have been studied both experimentally and analytically (see references (1) and (2)). The application of these data to blast in partially vented enclosures, however, is subject to some uncertainty, particularly when undetonated volumes of charge are an appreciable fraction of the enclosure volume. The tests described herein were conducted to furnish directly applicable data and to provide a better understanding of phenomena involved.

The tests were designed to furnish data for use in the explosive storage dividing wall problem. Various items containing high explosive charges are commonly stored in spaces which are separated from adjacent storage spaces by dividing walls. The primary purpose of the dividing wall is to prevent chain detonation in case of the detonation of any stored item. For economy of required storage facility and land it is desirable to set the explosive storage limit as high as possible consistent with the prevention of chain detonations. Full scale tests have revealed the incorrectness of previously made estimates of explosive storage limits. Thus there are at least two problems involved: one is to predict what the explosive limit for a given design will be; the other is to design for larger explosive limits, either by modification of storage spaces in being, or by new construction.

Storage facilities are commonly constructed in the form of a row of rectangular cubicles of reinforced concrete with roofs and one wall of relatively light construction designed to blow away quickly in case of explosion. The proper design of these cubicles has been hampered by the paucity of data on the amount and distribution of blast impulse, in case of explosion, to the walls dividing one cubicle from adjacent cubicles. This impulse will, of course, be affected by a number of variables of differing importance. The tests described herein were simplified to include only those variables considered to be of major importance.

The principal variables of this test were the charge size, the location within the enclosed space, and the shape of the enclosed space. The tests were conducted using 1/4 scale models of a typical storage cubicle, both unmodified and with two modifications: one modification being a three-eighth reduction in height of all walls,

the other a doubling of the width of the cubicle with no change to other dimensions. The cubicles were scaled only in their dimensions; no attempt was made to simulate wall masses, strengths or response characteristics. The walls were made of steel and were relatively more massive than their concrete counterparts. They were essentially free to move, being held in position only by their own inertia and the friction between their bottom edges and the steel plate upon which they rested. The design was such that the walls (effectively) would begin to move only after pressure levels had dropped below the point at which significant additional pressure would be imparted.

Amount and distribution of impulse delivered to the walls were measured both by the motion of the wall itself, and by the use of flying plug gages. The flying plug gages were aluminum cylinders fitted loosely into holes distributed over the surface of the vertical walls. One end of each cylindrical plug was positioned flush with the interior surface of the wall. Upon detonation of the charge each plug acquired a velocity directly proportional to the total impulse per unit area at its particular location. By photographic measurement of the velocity of the plug of known mass, its momentum could be determined. This momentum is equivalent to the total impulse imparted to the plug. As a check, the motion of the entire steel plate, both translational and rotational, gave a measure of the total impulse received by the wall.

The data obtained in these tests are presented herein, with a description of analytical procedures used. Several internal checks of data consistency were made. For example an estimate of the total impulse delivered to the wall was made directly from the plug gage data and compared with the total impulse as measured directly from the plate motion.

DESCRIPTION OF THE TESTS

Explosive Charges

All charges were cast in spherical molds from vacuum-mixed pentolite (50/50 ± 1% PETN/TNT). A hole was provided for single point central initiation by means of a U. S. Engineer's Special

Electric Blasting Cap. Four sizes of 1/6-scale charge were used. They were chosen to represent full scale weights ranging from 300 to 2000 pounds in a typical size of storage cubicle in current use. Thus their diameters were scaled in the ratio 1/6, and their weights in the ratio $(1/6)^3$. The intermediate weights were chosen so as to provide a geometrical progression constant of 1.88. Reduced and full scale weights are compared in the following table:

Pentolite Charge Weight (50/50 ± 1%; PETN/TNT)

Full Size	300 lbs.	564 lbs.	1060 lbs.	2000 lbs.
Small Scale	1.39 lbs.	2.61 lbs.	4.91 lbs.	9.26 lbs.

Cubicle Enclosures

All enclosures were constructed using 2-inch thick steel plates with square edges. Three, or less, of these plates were stood on edge in a U-shaped plan, as viewed from above, upon a heavy steel plate lying on the ground. Their arrangement and dimensions are shown in Figure 1. The interior dimensions of the scaled enclosure designated Type C are one-sixth those of a full-size storage cubicle having this same designation. The dimensions of the scaled enclosure designated half "C" were those of the same cubicle with heights of walls reduced in the ratio 3/8. The dimensions of the double "C" enclosure were those of the Type "C" except that the width was doubled.

Impulse "Flying Plug" gages

The plug gages used for impulse measurements were cylinders 1 inch in diameter by one inch long, machined from 2061 round aluminum bar stock. They were positioned in drilled holes in the wall plates as shown in Figure 1. To reduce binding or friction, a hole 1-1/2 inches in diameter was drilled 1-3/4 inch deep from the outside of each 2 inch thick steel plate. This provided a ledge 1/4 inch in thickness to support the innermost end of the plug. The plugs were carefully fitted for each test to provide freedom of motion with a minimum clearance. A light coating of silicone grease was used for lubrication.

Charge Location and Support

In each test a single charge was supported so that its center was in line with some intersection of normals from two or more plug positions. Thus, as may be seen in Figure 1, there were nine such

possible charge positions in the two larger cubicles and six such possible positions in the smallest. The charges were suspended in the selected position from a light metal rod lying across the top of the cubicle. The three smaller sizes of charge were suspended in a light nylon mesh hair net. The 9.3 pound spheres were supported by 2 inch wide strips of nylon mesh. Positions of the charges were maintained to within ±1/4 inch of the selected point.

Instrumentation

Three 16mm Fastax cameras were used to record motion of both the flying plug gages and the wall itself. The arrangement of cubicles, cameras and background grids may be seen in Figure 1A. To avoid the obscuring effect of explosive products, it was necessary to position the grids several feet away from the cubicles in the direction of plug flight. The entire flight of the plugs could not be followed, therefore, and thus it was necessary to positively identify each plug with its original position in the wall by a separate means. The use of color film, color coding of plugs and careful focusing of cameras on the expected path of the plugs made positive identification possible, even with the largest number of plugs used. The reference grids had a white background with 1/8 inch wide lines, two inches apart. Translational velocity of the center of mass of each plug and the walls was computed from displacement vs time measurements on the film and converted to impulse.

Impulse Measurements

The computation of impulse received by individual plugs and by each wall was based on the following:

From Newtons second law $$F = m\frac{dv}{dt}$$

$$Fdt = mdv$$

For a point mass the impulse $$I = \int_0^{t_1} Fdt$$

Since the plug has a finite area A over which a force or pressure P is applied then by definition the impulse is:

$$I = \int_0^{t_1} P \, dt$$

but $P = F/A = m\ddot{x}/A$

$$\text{then } I = m/A \int_0^{t_1} \ddot{x}(t)dt = \frac{m\,\dot{x}(t_1)}{A}$$

The time duration t_1 is the period during which the shock pressure P is applied to the cubicle wall. This analysis requires the assumption that $x \doteq o$ during the period o to t_1; cor[illegible]derations discussed below indicate that this assumption is rea[illegible]ble.

An analysis of maximum errors in impulse resulting from air drag and measurement error may be found in Appendix B.

Results and Discussion

Values of the impulse received at selected points of the wa[illegible]l for the various test conditions are shown in Figures 2 through 23. Examination of these data reveals that in general there is satisfactory reproducibility and self-consistency of results. In cases where a charge is located symmetrically with respect to two walls the same impulse would be expected at equivalent points. The spread in these values is indicated on a number of the graphs. A similar spread of values is indicated in several instances where tests were repeated. Self-consistency is indicated by the similarity of patterns of distribution of impulse as charge weight is varied, holding other parameters constant.

As an additional check upon the errors in the data, values of total impulse for individual plates were determined by two independent means. The total momentum (and hence applied impulse) of the plate, since its mass was known, could be determined quite easily from velocity of its center of mass. The total momentum of the plate was estimated from plug gage data by fitting of the data to response surfaces through multiple regression analysis. The response surfaces were then integrated to obtain total impulse. Some uncertainty is

involved in the process since the distribution of impulse outside the measured points is not known, and may change drastically, as for instance by corner reflection. The numbers used for comparison were obtained by assuming the average of the impulse within the area bounded by known values, would be the average for the entire plate. The comparisons could be made for a rather large number of the total values, and are shown in Appendix A.

It will be noted that the total impulses calculated from the data points are generally somewhat smaller than those measured from the motion of the entire plate. In a few cases, however, this is reversed and a few agree quite well. It would be possible, though it was not done because of lack of time, to make additional checks using the rotational velocity of the plate. A procedure has been worked out to do this. This would give some information as to the distribution of impulse which could be used for better fitting of data points to response surfaces.

CONCLUSIONS

The use of modeling for measurement of the magnitudes and distribution of impulse in partially vented enclosures is a practical procedure. Variation of parameters other than the ones used in this study could easily be done. For instance, frangible tops or fronts could be included or a variety of shapes could be employed. In a number of cases a sufficiently good measure of magnitude and distribution of impulse might be obtainable from motion of the entire plate mass for considerably less effort in data reduction than with the plug gages. Further simplification of the plug gage procedure might also be possible, such as by use of electronic velocity measurement instead of the use of camera.

REFERENCES

1. Johnson, O. T., Patterson, J. D., II, and Olson, W. C., "A Simple Mechanical Method for Measuring the Reflected Impulse of Air Blast Waves", BRL Memorandum Report No. 1088, Aberdeen Proving Ground, Maryland, July 1957
2. Dewey, J. M., Johnson, O. T., Patterson, J. D. II, "Mechanical Impulse Measurements Close to Explosive Charges", BRL Report No. 1182, Aberdeen Proving Ground, Maryland, November 1962.

TOTAL WALL IMPULSE MEASUREMENTS

Fig. No.	Test No.	Wall Impulse (PSI-millisec) (Calculated/measured) Plate A		Plate B		Plate C		Plate Velocity (ft/sec) Plate A	Plate B	Plate C
2	37		568		555		943	35.3	34.5	
	43		1006		1027		1588	62.3	63.8	93.6
	77		--		--		5653	--	--	333
3	39		543		543		673	33.7	33.7	39.8
	45		986		1006		1265	61.2	62.5	74.6
	66		--		--		4036	200	214	238.1
4	41		483		483		551	30	30	32.5
	81		2012		2415		3110	125	150	--
5	36		700		474		909	43.5	29.4	53.6
	42		1271		911		1582	78.9	56.6	93.3
6	38		680		483		717	42.3	30.0	42.3
	44		1208		847		1282	75.0	52.6	75.6
	129		-		--		892	--	--	52.6
7	40		653		424		560	40.5	26.3	33.0
	46		1150		644		1116	71.4	40.0	65.6
	80		3715		--		3370	231	--	198.7
8	22		634	328	416		733	37.5	24.6	35.3
	144	741	474	328	441	537	776	28.0	26.1	37.5
	31	--	--	520	--	882	1310	--	--	63.3
	141	270	831	--	--	882	1252	49.2	--	60.5
	86	314	--	872	--	1206	--	--	--	--
	91	514	--	872	--	1206	--	--	--	--
9	20	355	334	355	350	581	565	--	--	--
	137	355	350	355	340	581	582	24.4	23.4	32.4
	35	594	--	594	--	1000	1519	--	--	73.4
	142	594	--	594	--	1000	1209	--	--	58.4
10	138		393	--	433	603	811	23.3	25.6	
	34	642	--	642	1748	1011	1617	--	103.5	78.1
	143	642	831	642	--	1011	1735	49.2	--	83.8
	90	909	--	909	--	1357	2863	--	--	138.4
11	19	332	545	332	--	456	565	32.3	--	27.3
	88	812	--	912	--	1180	--	--	--	--
12	17	423	--	423	--	529	--	--	--	--
	33	582	--	582	--	--	1308	--	--	63.2
	87	960	--	960	--	1562	--	--	--	--
13	26	--	--	307	--	471	--	--	--	--
	136	594	453	307	343	471	590	26.8	20.4	28.8
	27	--	--	555	--	739	--	--	--	--
	140	--	845	--	--	739	1070	50.0	--	51.7
	83	1980	1491	963	--	1180	1621	88.2	--	78.3
14	33	--	--	330	--		--	--	--	--
	135		735	330	576	793		43.5	34.1	38.5
	30		--	553	685	1420		--	40.5	68.6
	139		874	--	792		1515	51.7	46.9	73.2
	82		1584	972	1207	2474		93.8	71.4	119
15	25		--	384	--	515	--	--	--	--
	28		--	509	--	949	706	--	--	34.1
	54		--	852	--	1496	2029	--	--	98.0

TOTAL WALL IMPULSE MEASUREMENTS (Continued)

Fig. No.	Test No.	Wall Impulse (PSI-millisec) (Calculated*/measured**) Plate A		Plate B		Plate C		Plate Velocity (ft/sec) Plate A	Plate B	Plate C
16	24		--	-	--	574	1124	--	--	56.3
	29		1036	-	--	932	1630	62.5	--	88.7
	85		--	-	--	3018	3196	--	--	134.4
17	50	273	421	227	579	187	--	19.3	26.6	--
	110	--	--	227	--	187	--	--	--	--
	55	472	817	486	589	354	553	37.5	27.0	29.1
	119	472	808	486	617	354	579	37.0	28.3	30.5
	92	855	--	788	--	639	--	--	--	--
	124	855	1557	788	1258	639	1139	71.4	57.7	60.0
	98	1423	1486	1372	--	1260	--	68.2	--	--
18	113	233	--	233	--	243	--	--	--	--
	117	491	--	491	--	540	617	--	--	32.5
	127	858	--	858	--	--	--	--	--	--
	106	1355	--	1355	--	856	--	--	--	--
19	114	335	--	335	--	373	357	--	--	18.8
	118	551	788	551	727	--	566	36.1	33.3	29.8
	128	1014	1453	1014	--	--	1582	66.7	--	83.3
20	112	222	--	222	--	220	--	--	--	--
	116	366	--	366	--	319	--	--	--	--
	126	702	--	702	934	--	--	--	42.9	--
	104	1020	--	1020	--	958	--	--	--	--
21	122	298	--	298	--	375	--	--	--	--
	115	437	--	437	--	354	--	--	--	--
	129	642	--	642	1028	--	--	--	47.6	--
22	48	273	711	199	--	200	--	32.6	--	--
	53	--	--	341	--	311	--	--	--	--
	121	849	--	514	--	648	946	--	--	49.8
	108	1580	2843	949	--	990	1624	130	--	85.5
23	49	290	425	264	594	--	--	19.5	27.3	--
	54	483	833	409	545	--	602	38.5	25.0	31.7
	120	929	1635	634	--	--	1117	75.0	--	58.8
	99		2180		--	--	1728	100.0	--	91.0
24	51	285	457	193	--	186	--	21.0	--	--
	56	437	818	349	436	509	570	37.5	20.0	30.0
	122	929	--	657	--	875	1035	--	--	54.5
25	107	--	--	--	--	--	--	--	--	--
	52	497	--	455	--	--	824	--	--	43.4
	123	--	1924	869	--	977	1472	88.2	--	77.5

*Calculated plate impulses are evaluated by fitting the plug impulse values to a "best" surface function and integrating over the plate area.

**Measured plate impulses are evaluated by observing plate velocity and mass and inserting these values in the equation $I = \frac{mV}{A}$ as was done to determine plug impulse.

ANALYSIS OF ERRORS OF DISTANCE, TIME AND VELOCITY

I. Errors in Plug Velocity - Air Drag

Since the velocity of the plug is measured as an average velocity over a region 4 to 7 feet through air from the starting point it is important to have an estimate of the ratio of the measured velocity to the true velocity. For air drag of a right cylinder:

$$\frac{dv}{dx} = -C_D \frac{A}{M} \rho v$$

where

v = velocity

x = distance

C_D = drag coefficient

A = presented area*

M = mass of cylinder

ρ = density of air

*A theorem of Cauchy's states that the presented area of a regular body flying with random tumbling equals one fourth of its total surface.

For a cylinder 1 inch diameter and 1 inch long $A = 3/8\pi \text{ in}^2$.

when:

$$C_D \cong .4 \text{ (for velocities under 1000 ft/sec)}$$

then:

$$C_D \frac{A}{M} \rho \cong 10^{-4}$$

$$x = 183 \text{ cm (six feet)}$$

$$\frac{dv}{dx} \cong -10^{-4} v$$

$$\ln v = -10^{-4} x + c$$

$$v = Ke^{-10^{-4}x}$$

$$\text{at } x = 0,\ v = Vo = K \text{ so } v = Vo\ e^{-10^{-4}x}$$

$$v > 0.98\ Vo$$

II. Error in Plug Velocity - Time and Distance

The maximum uncertainty of plug motion with regard to time, U_t is 1/8th millisecond and with regard to distance, U_x is 2 inches and x is 36 inches. Applying the rule for total differentiation of a function of 2 variables for

$$v = \frac{x}{t} \quad \text{and} \quad dv = \frac{\partial v}{\partial x}\,dx + \frac{\partial v}{\partial t}\,dt$$

or

$$dv = \frac{dx}{t} + \frac{-x\,dt}{t^2}$$

Given:

$$U_v = \left|\frac{U_x}{t}\right| + \left|\frac{-xU_t}{t^2}\right|$$

$$\frac{U_v}{v} = \left|\frac{U_x}{x}\right| + \left|\frac{-U_t}{t}\right|$$

$$\frac{U_x}{x} = \frac{2}{36} = 5.6\%$$

$$\frac{U_t}{t} = \frac{1/8}{t}$$

For very fast plugs t can be as low as 2 msec.

Then

$$\frac{U_t}{t} = \frac{1/8}{2} = 1/16 = 6\text{-}1/4\%$$

Maximum error < (5.6% + 6-1/4%) = < 12%

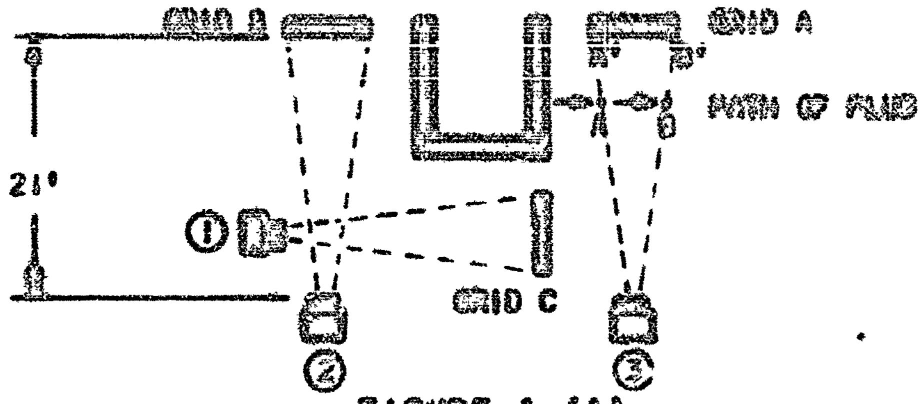
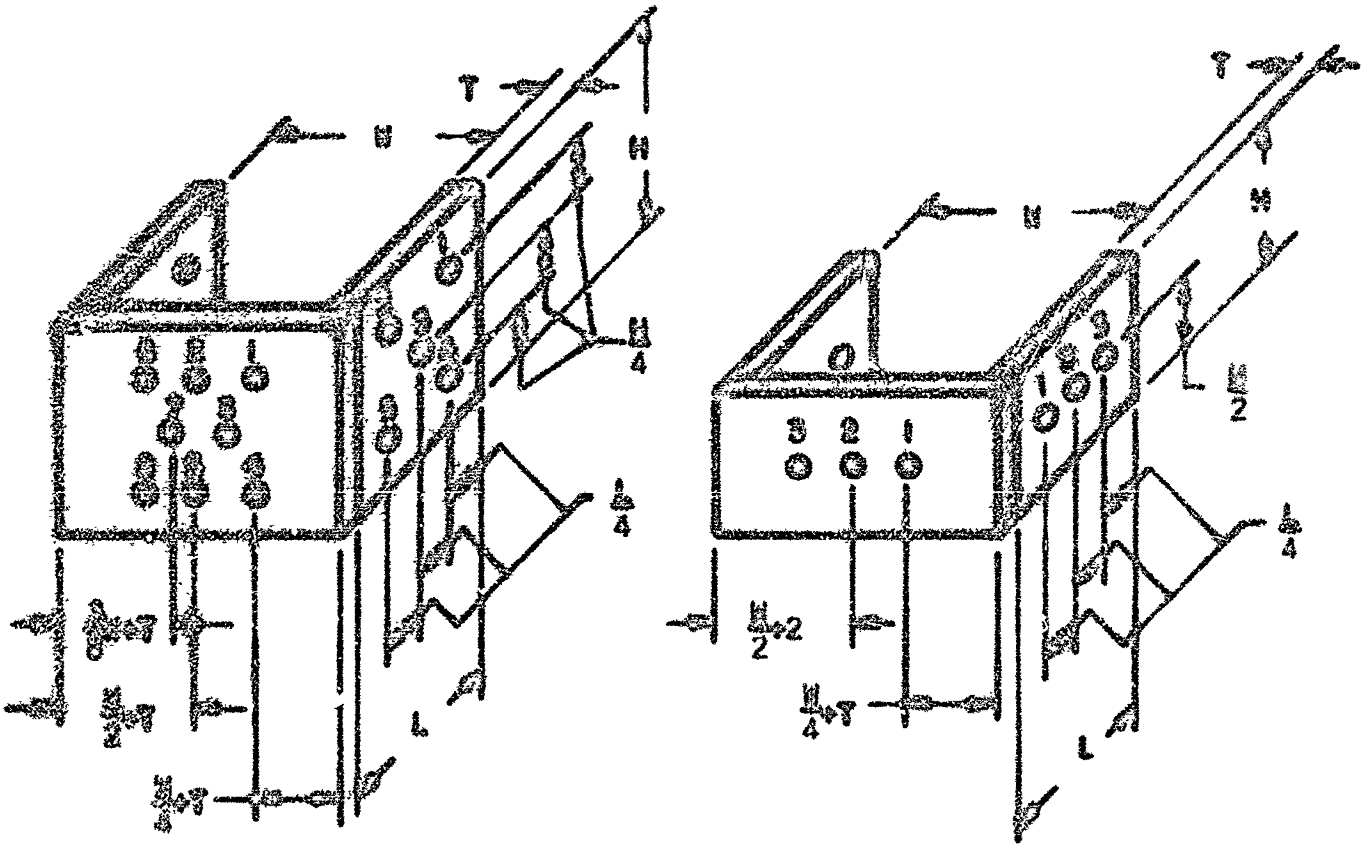


FIGURE 1 (A)



TYPE C AND 2C

TYPE ½C

FIGURE 1 (B)

	TYPE C	TYPE 2C	TYPE ½C
W	17"	36"	17"
H	16"	16"	16"
L	22"	22"	22"

FIGURE 1

A SKETCH OF THE TEST ARRANGEMENT OF CUBICLE, CAMERAS AND [illegible] GRIDS AND THE WALL DIMENSIONS AND PLUG POSITIONS OF THE THREE CUBICLE DESIGNS.

TYPE HALF "C" CUBICLE

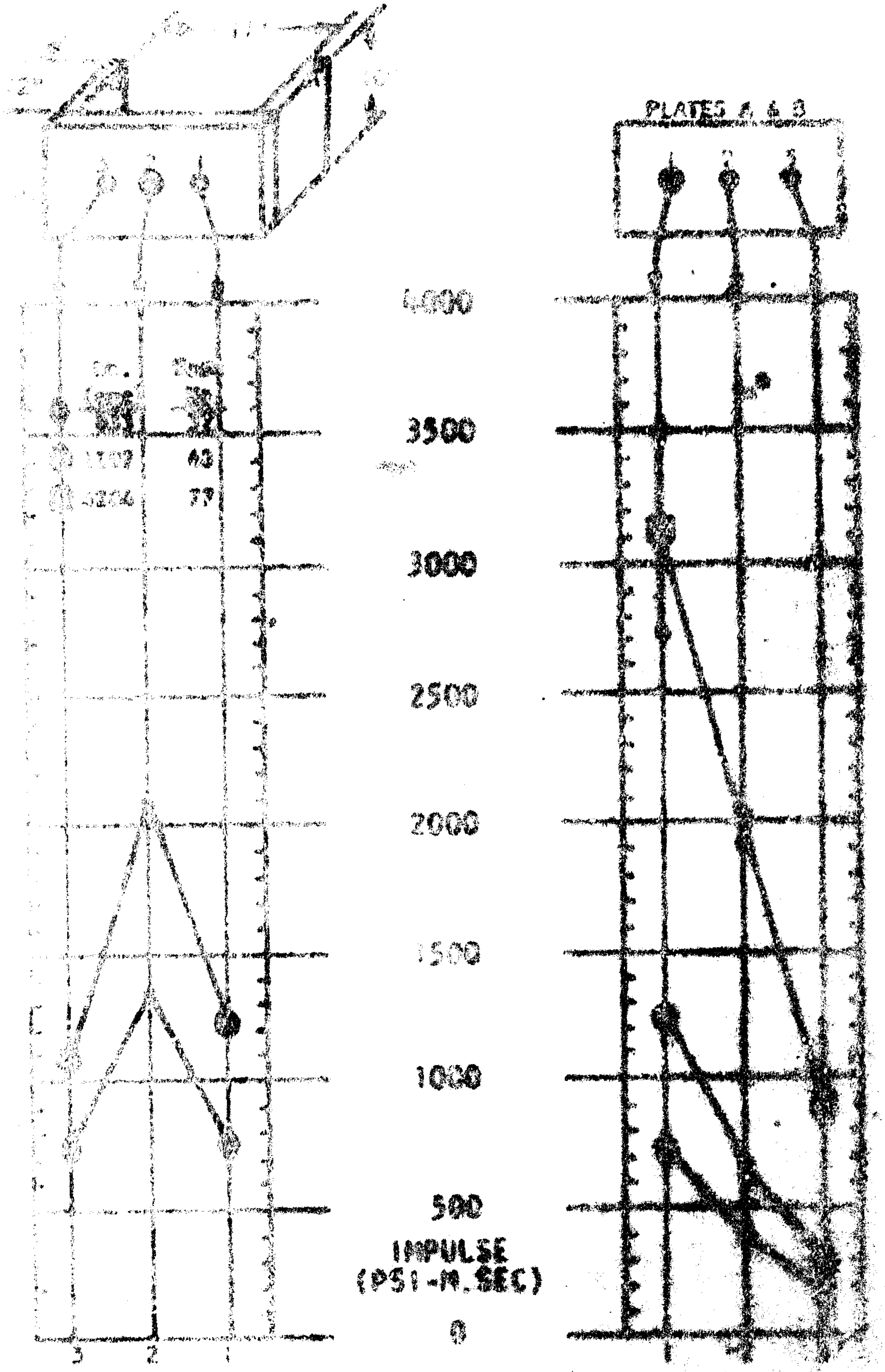
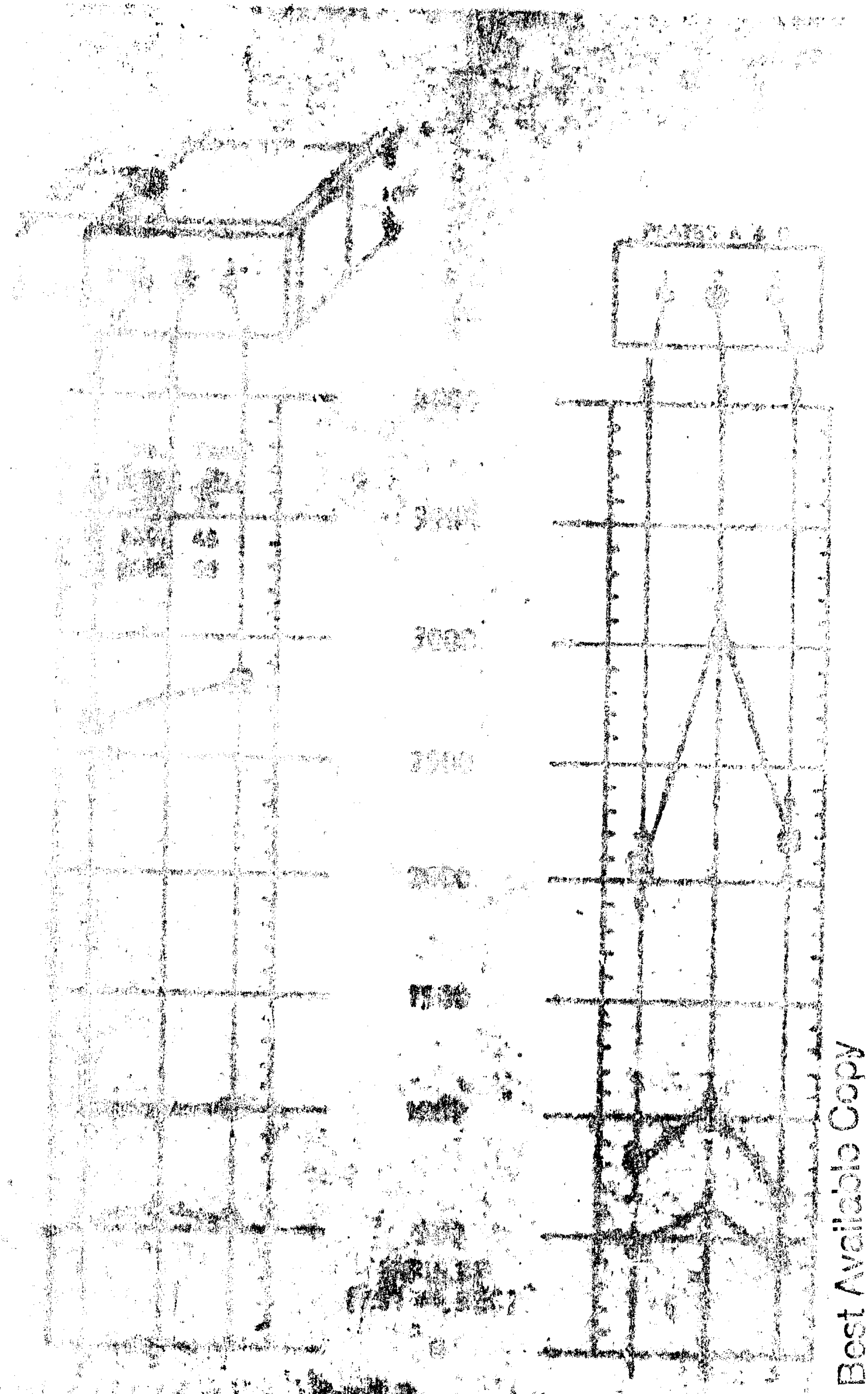
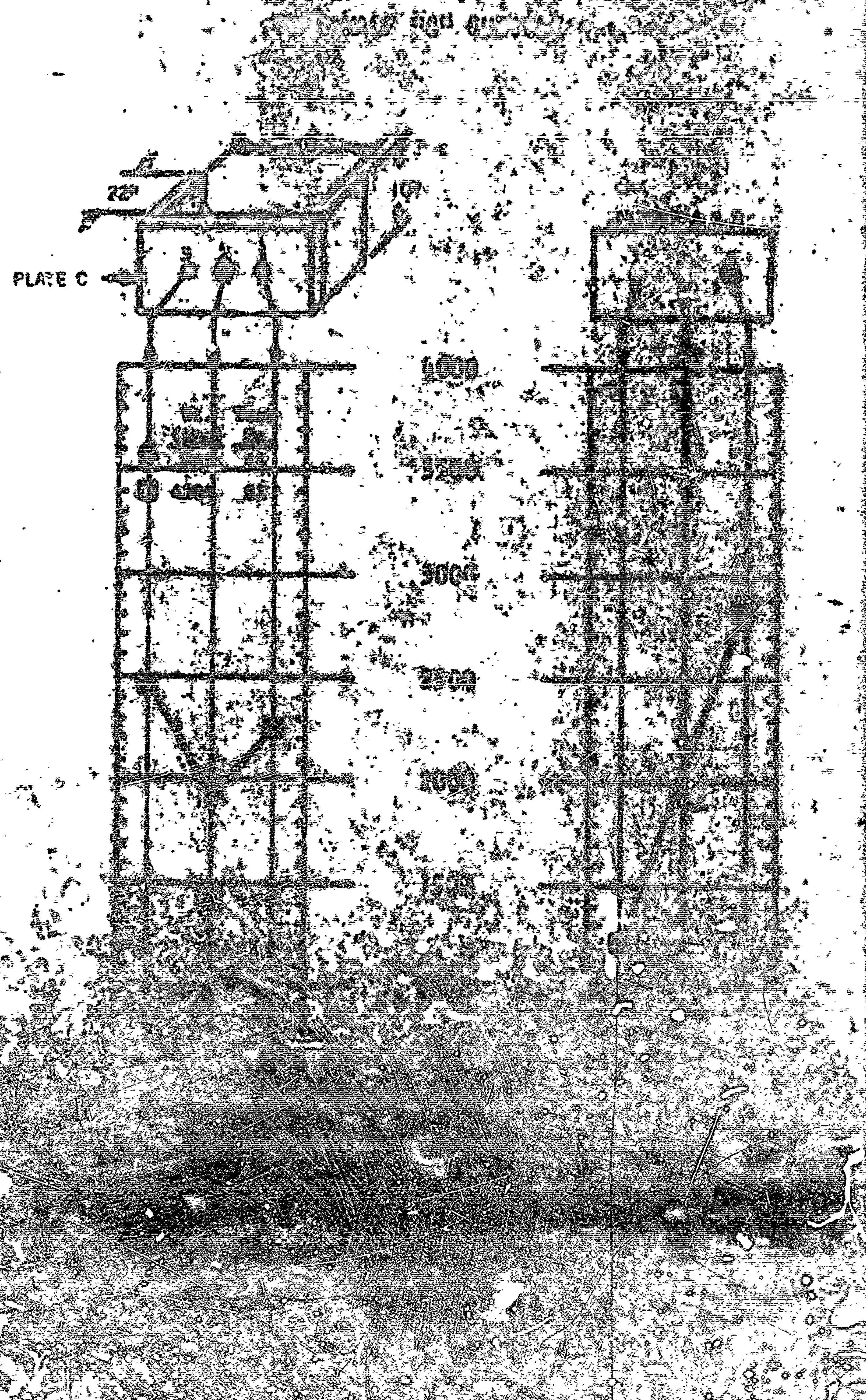


Figure 2

[illegible] values at pressure points on the 3 walls [illegible]
[illegible] exploding pentolite spheres placed at the [illegible]
[illegible]


PLATES A & C



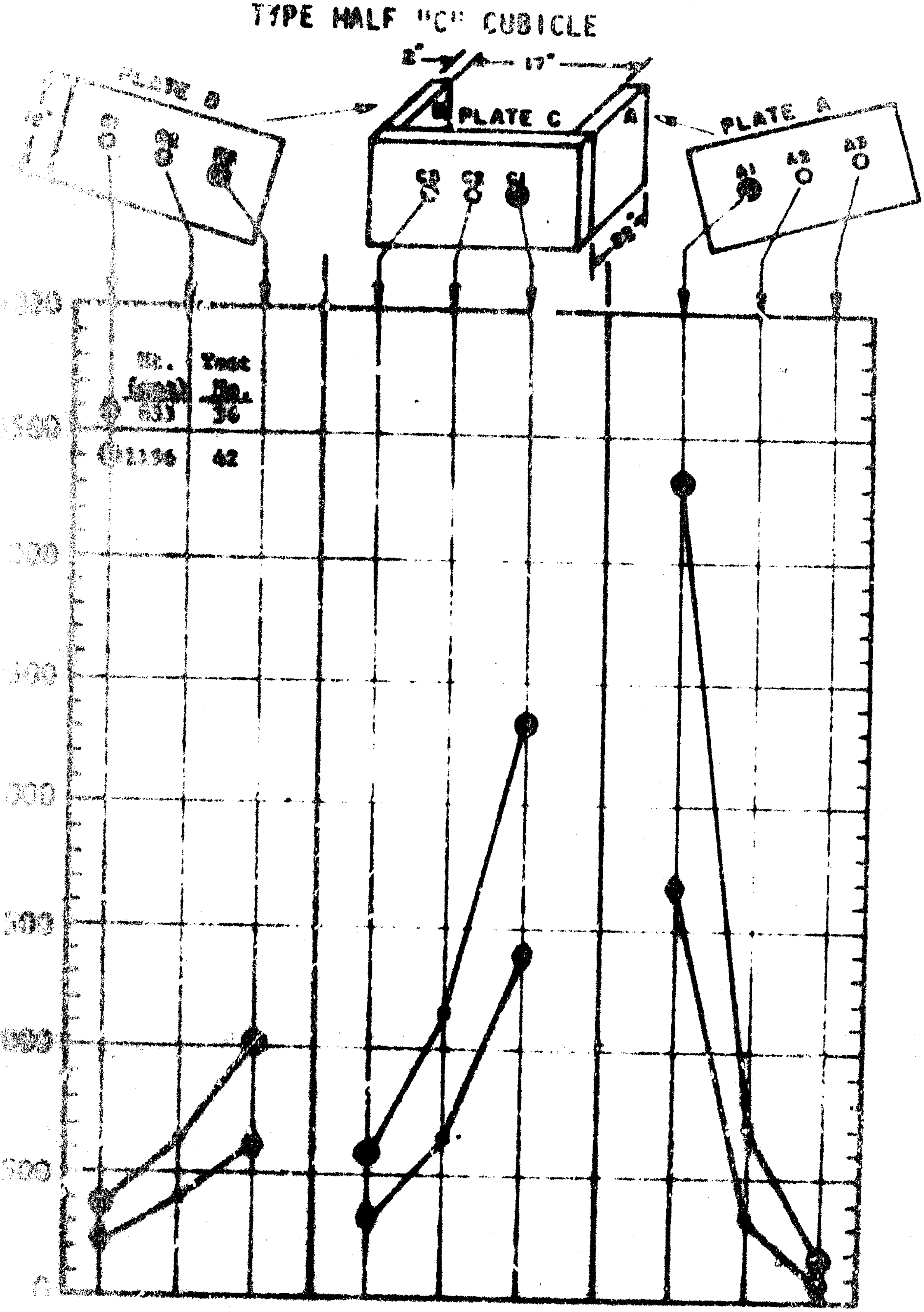


Figure 5
Impulse values at discrete points on the 3 walls from centrally [illegible] [illegible] spheres placed at the intersection of the [illegible] of the [illegible] plate.

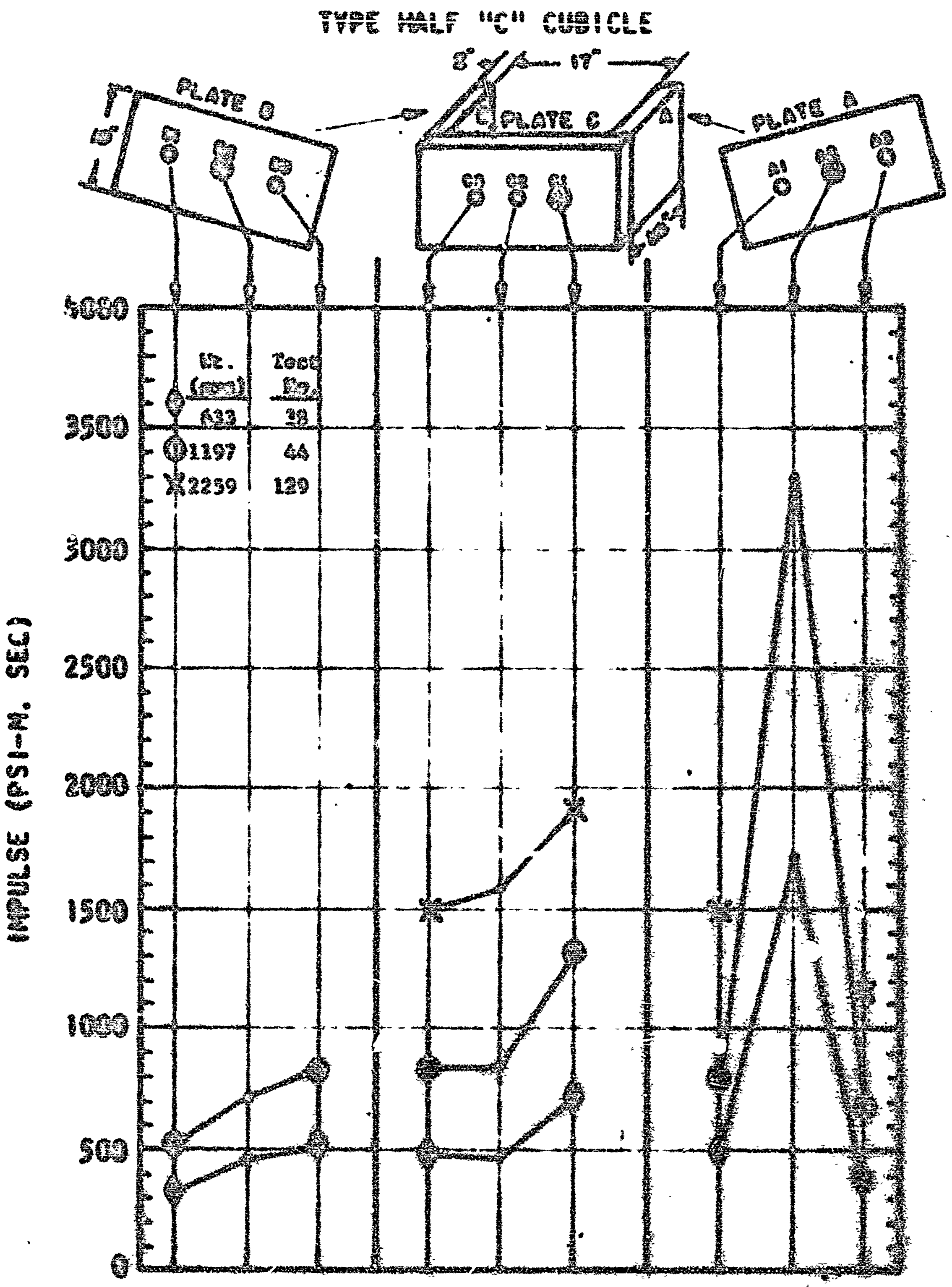


Figure 6
Impulse values at discrete points on the 3 walls from centrally initiated exploding pentolite spheres placed at the intersection of the normals of the shaded plugs.

TYPE HALF "C" CUBICLE

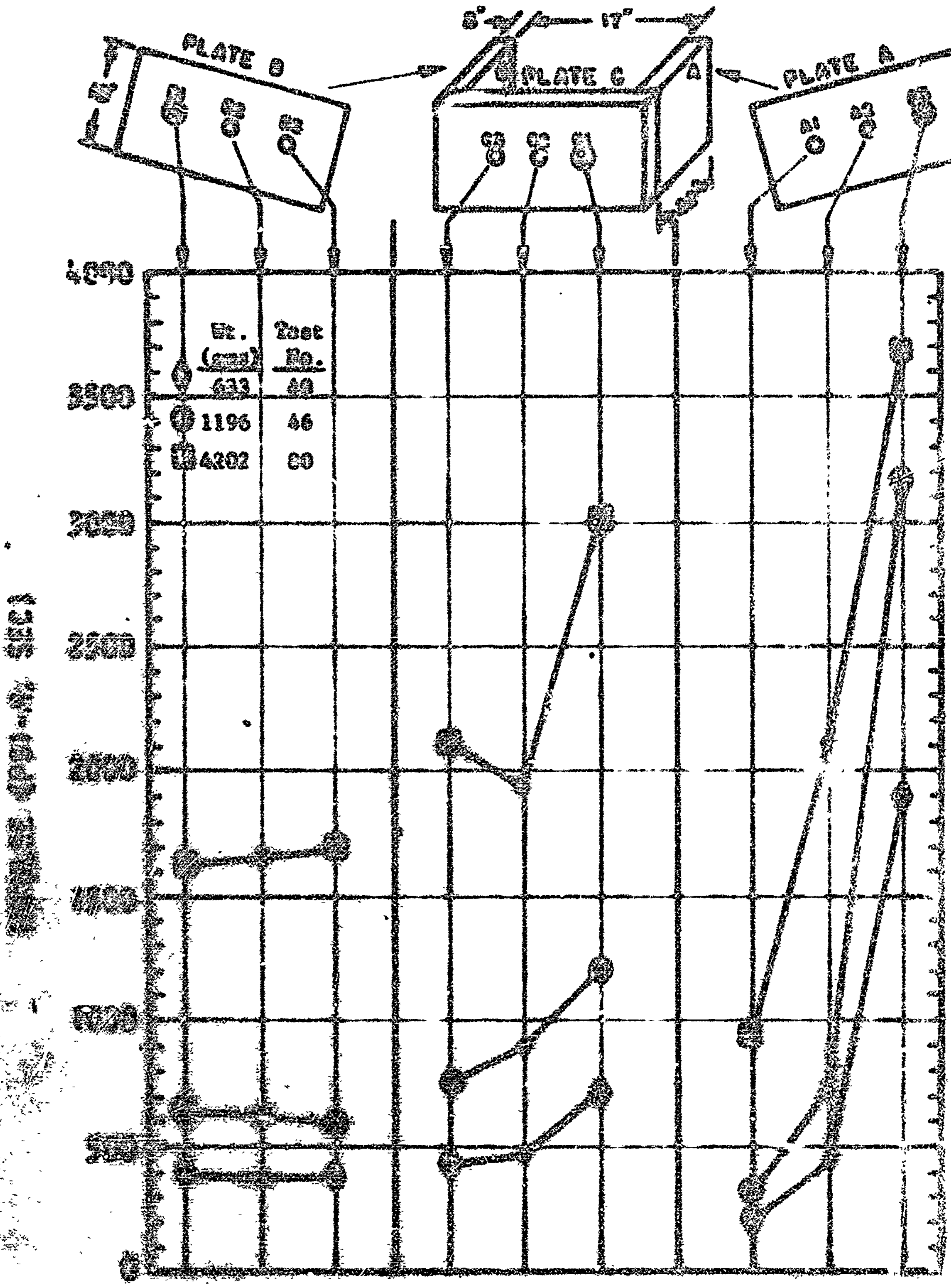


Figure 7
Impulse values at discrete points on the 3 walls from centrally [illegible] exploding pentolite spheres placed at the intersection of the [illegible] of the [illegible].

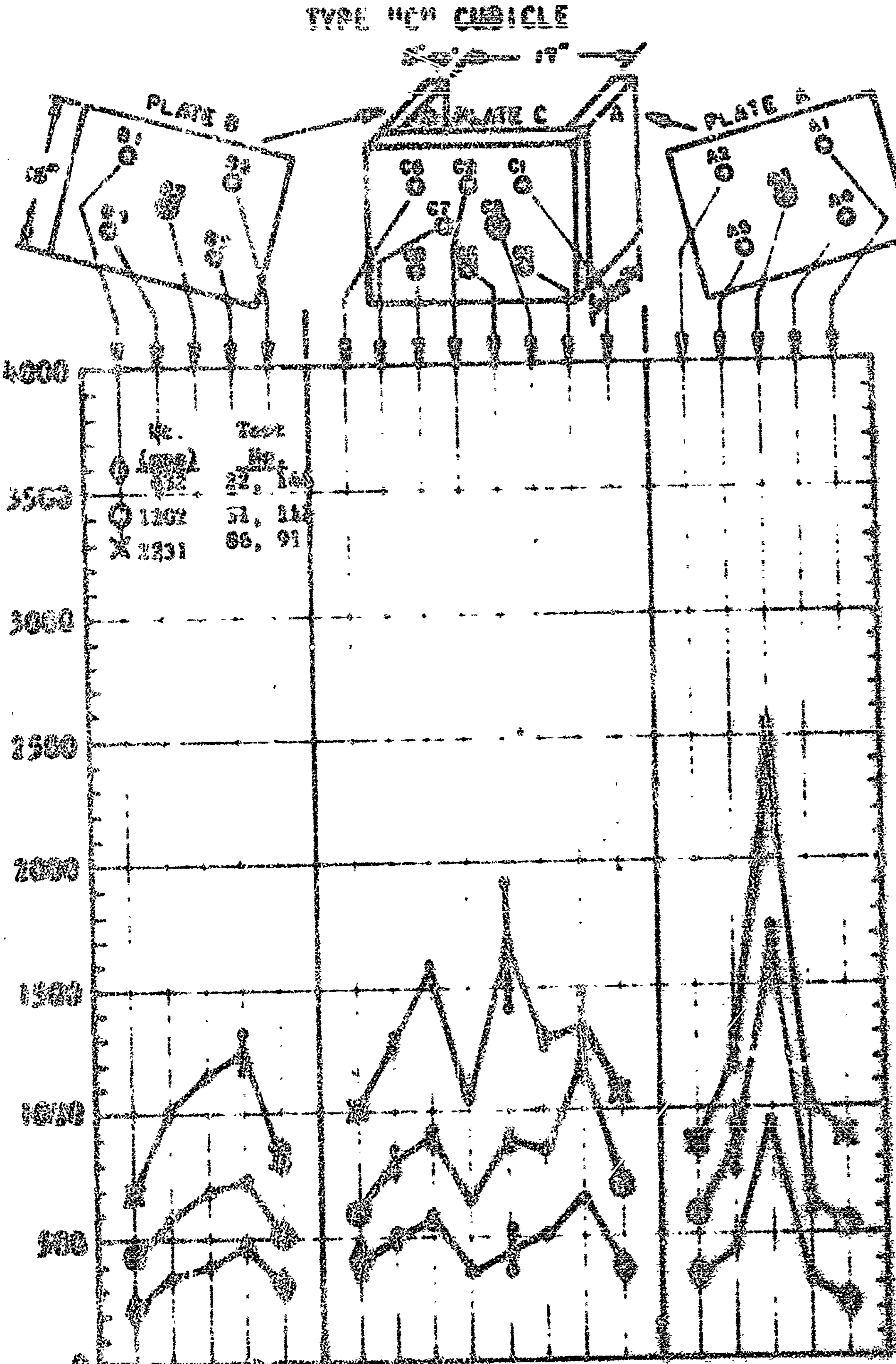
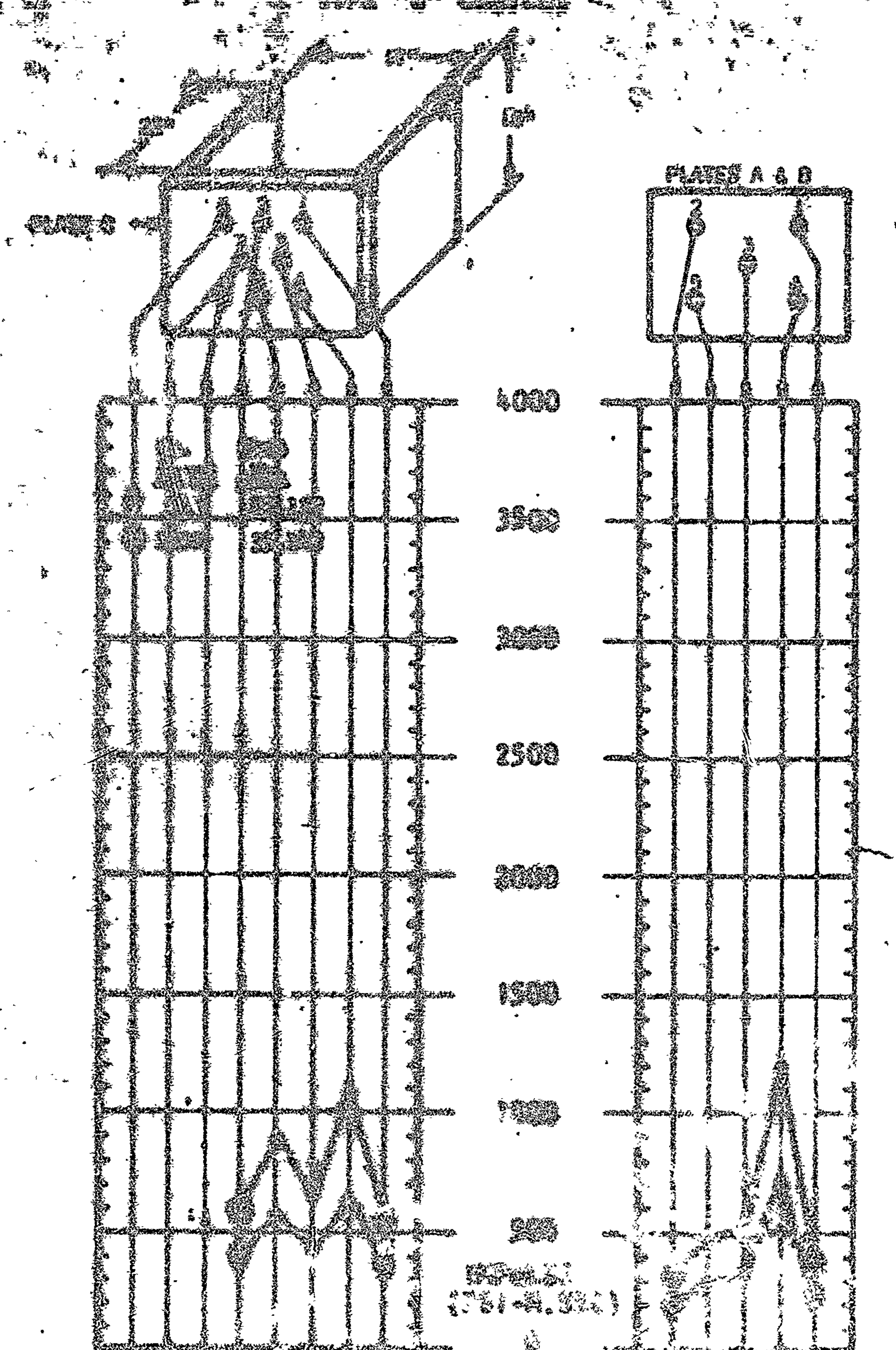
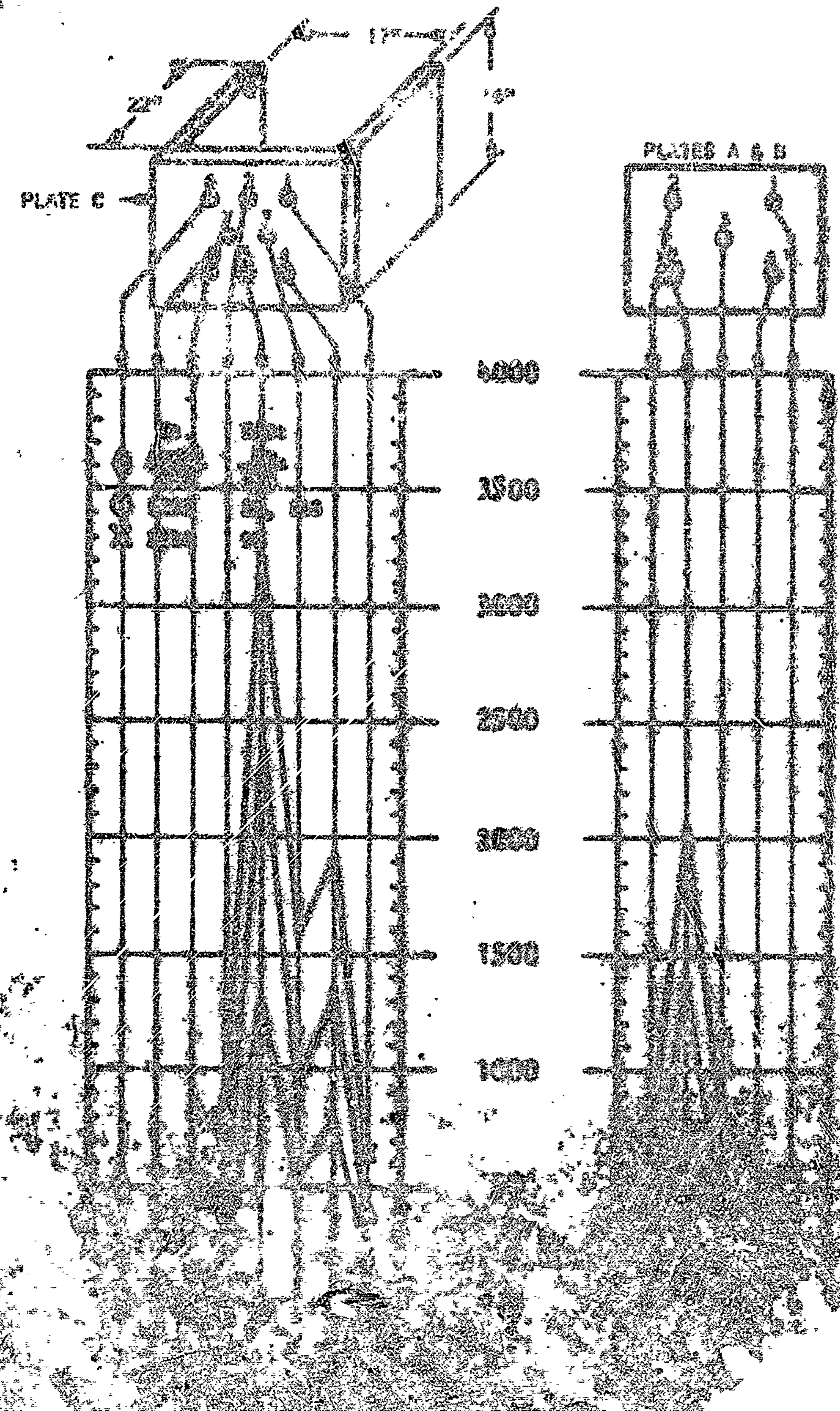


Figure 8
Impulse values at discrete points on the 3 walls from centrally detonated exploding pentolite spheres placed at the intersection of the normals of the cubicle plates.


PLATES A & B
4000
2500

[illegible]

TYPE "C" CUBICLE



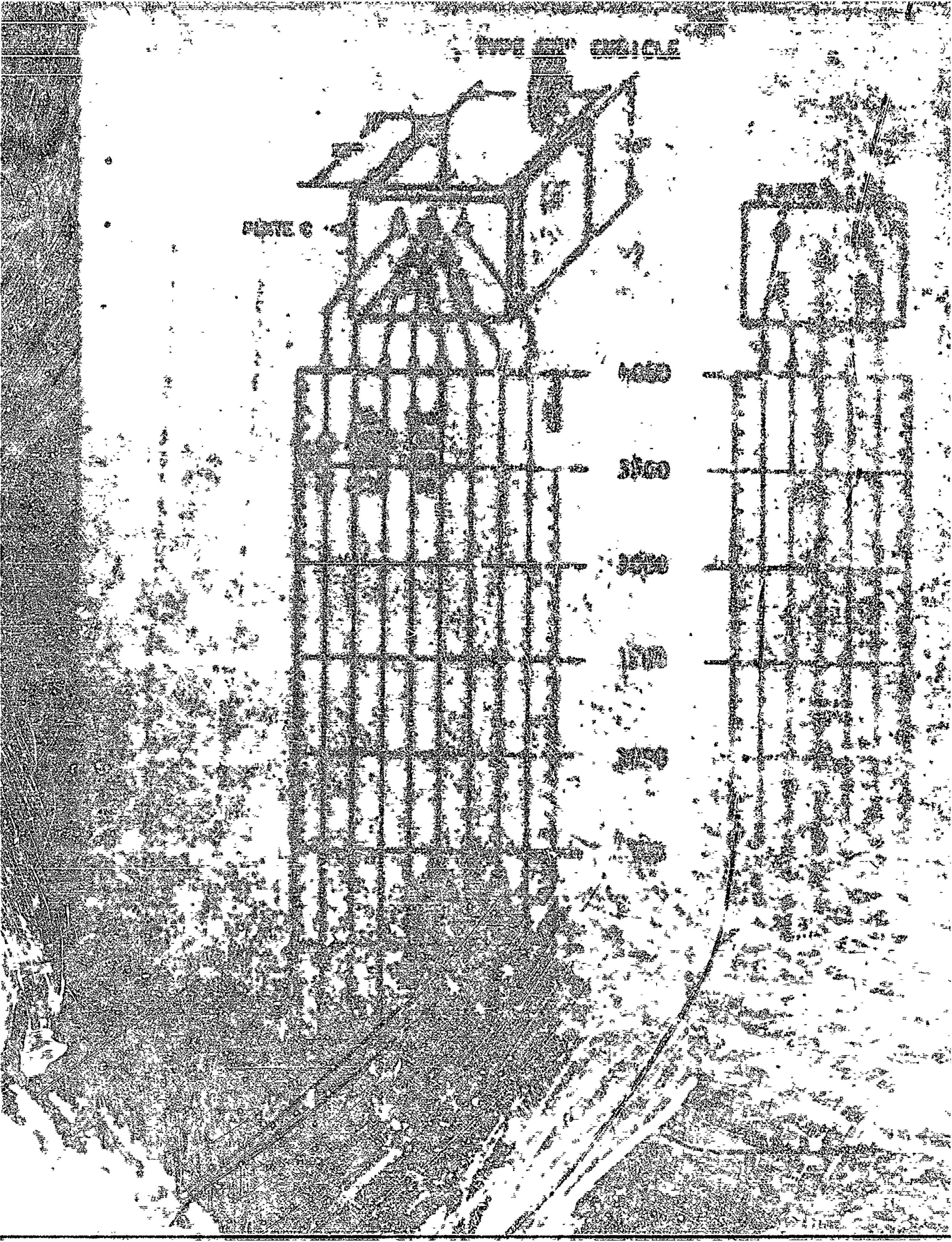
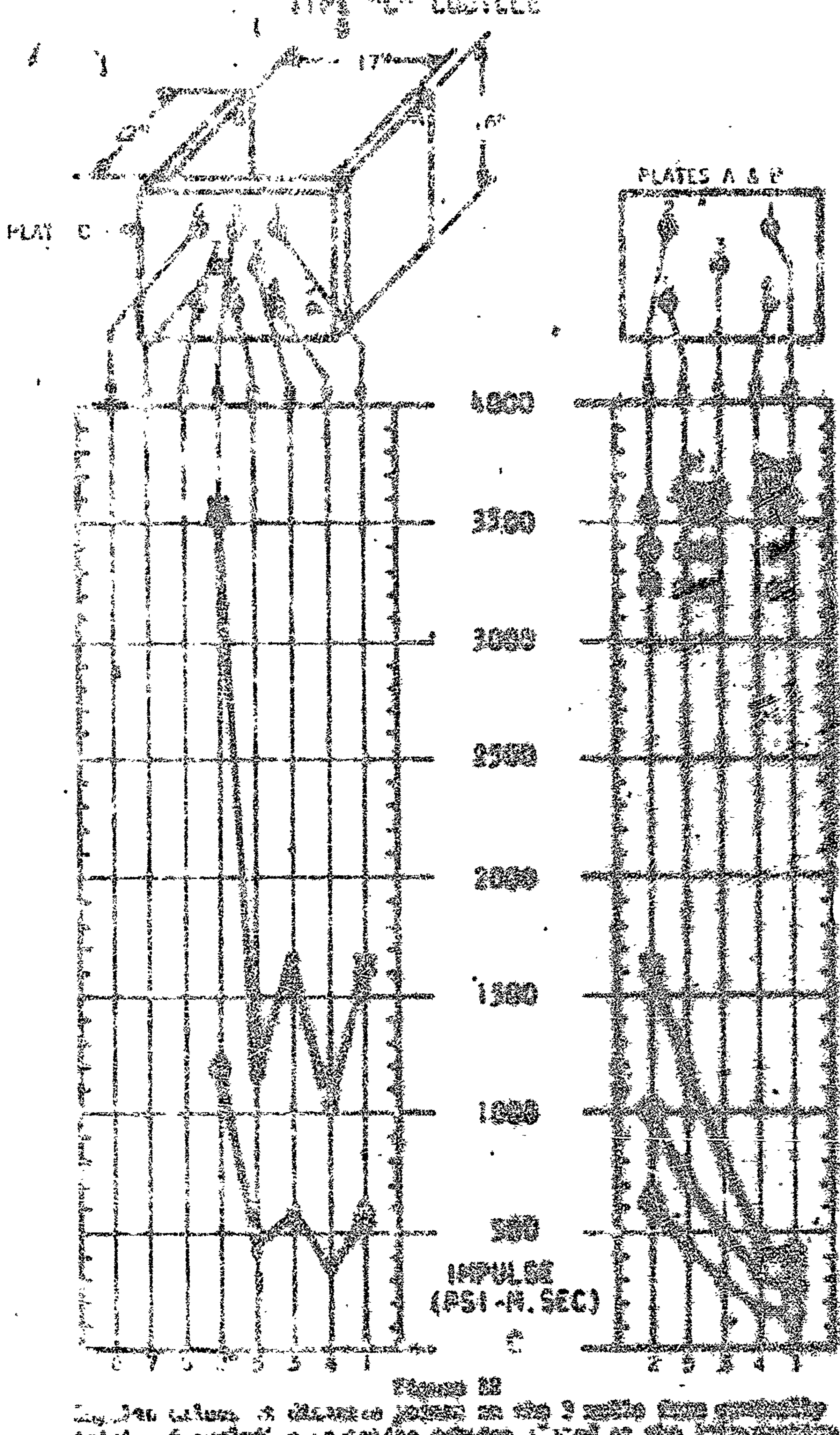


PLATE 6
3500



TYPE "C" CUBICLE
PLATES A & B
4000
3500
3000
2500
2000
1500
1000
500
IMPULSE
(PSI-M. SEC)

Figure 22

TYPE "C" CUBICLE

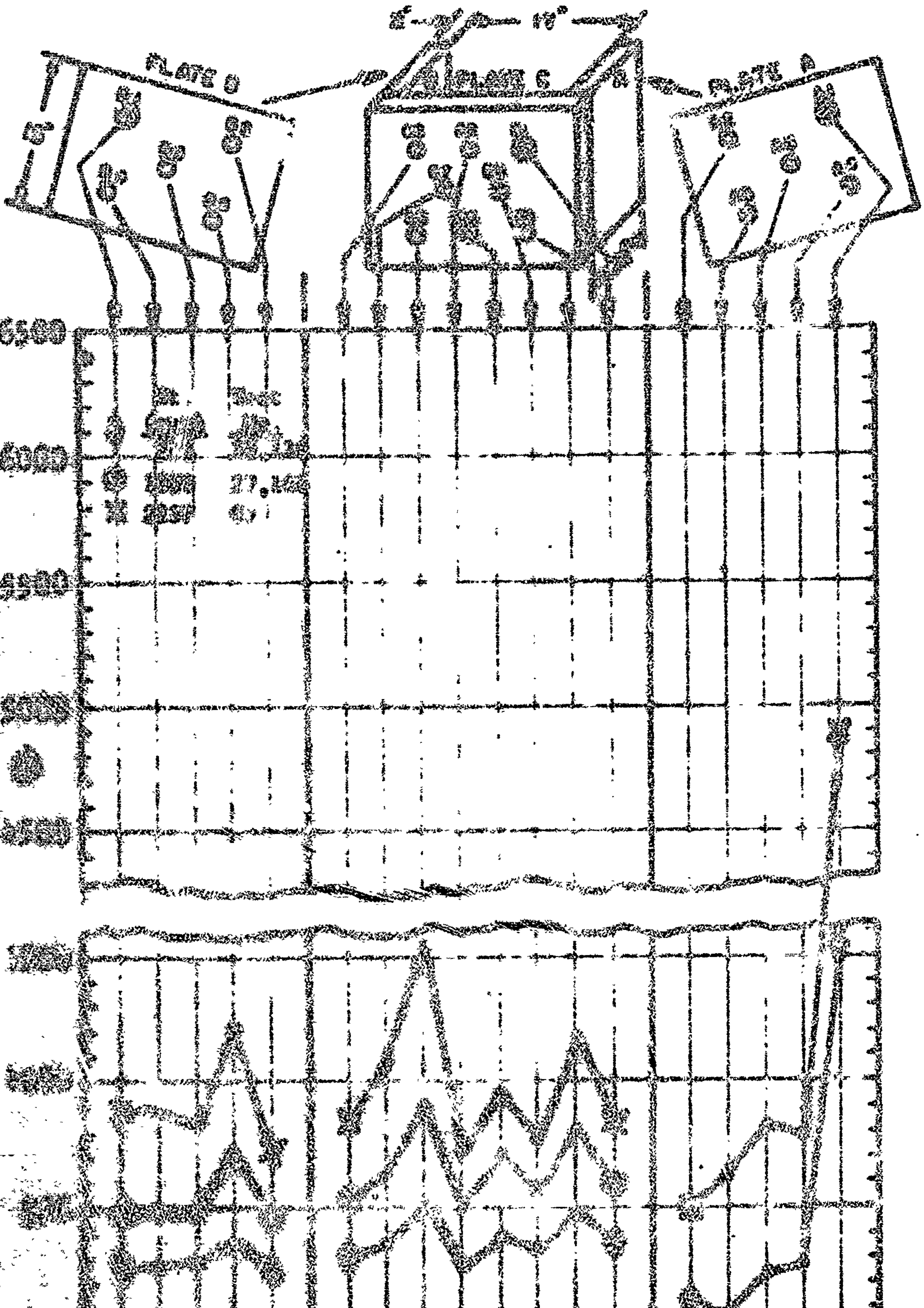


Figure 13

[illegible] at the 3 walls from centrally [illegible] was placed at the intersection [illegible]

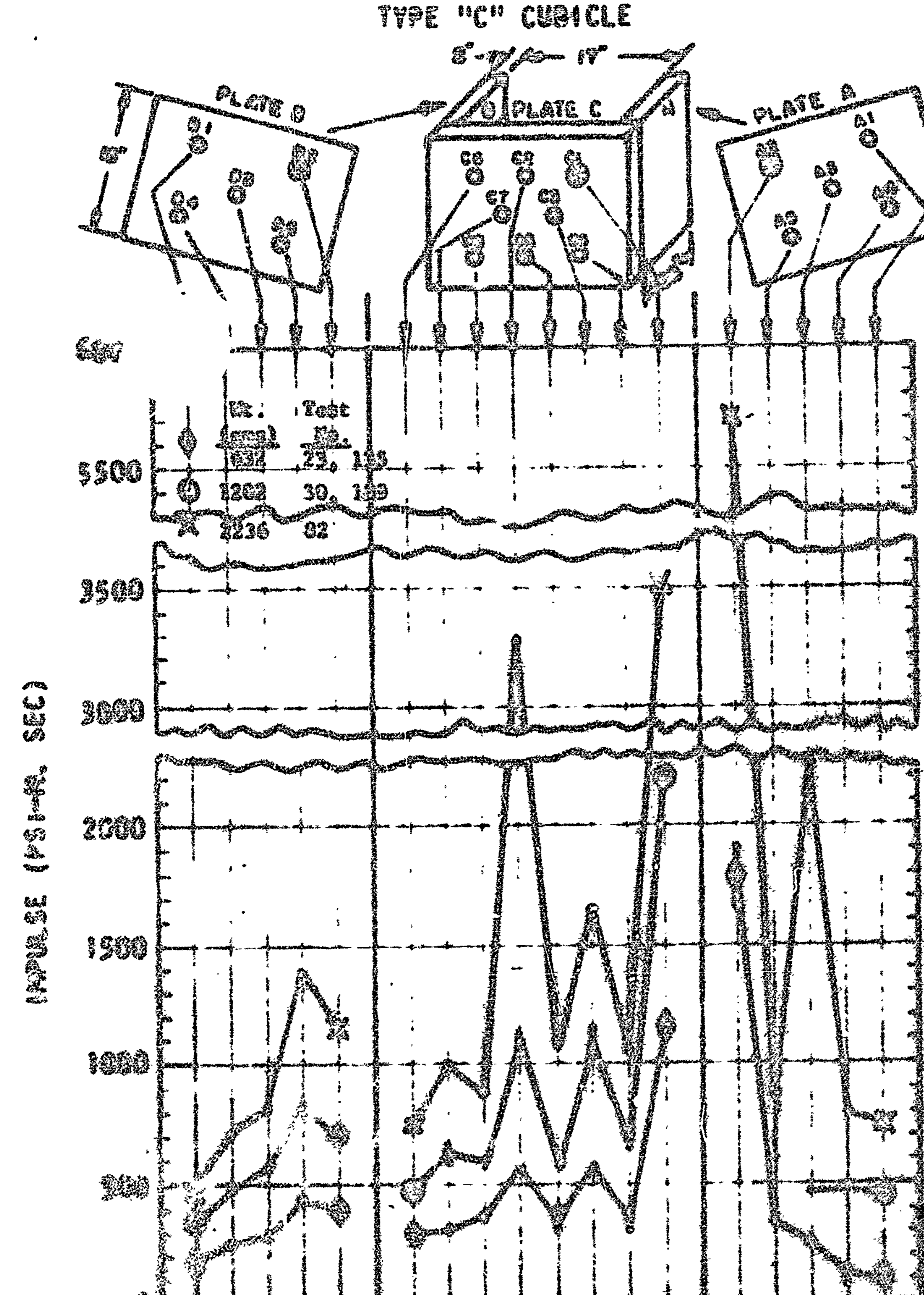


Figure 14

Impulse values at diverse points on the 3 walls from [illegible] [illegible] [illegible] pentolite spheres plotted at the intersection of the [illegible] of the [illegible] plugs.

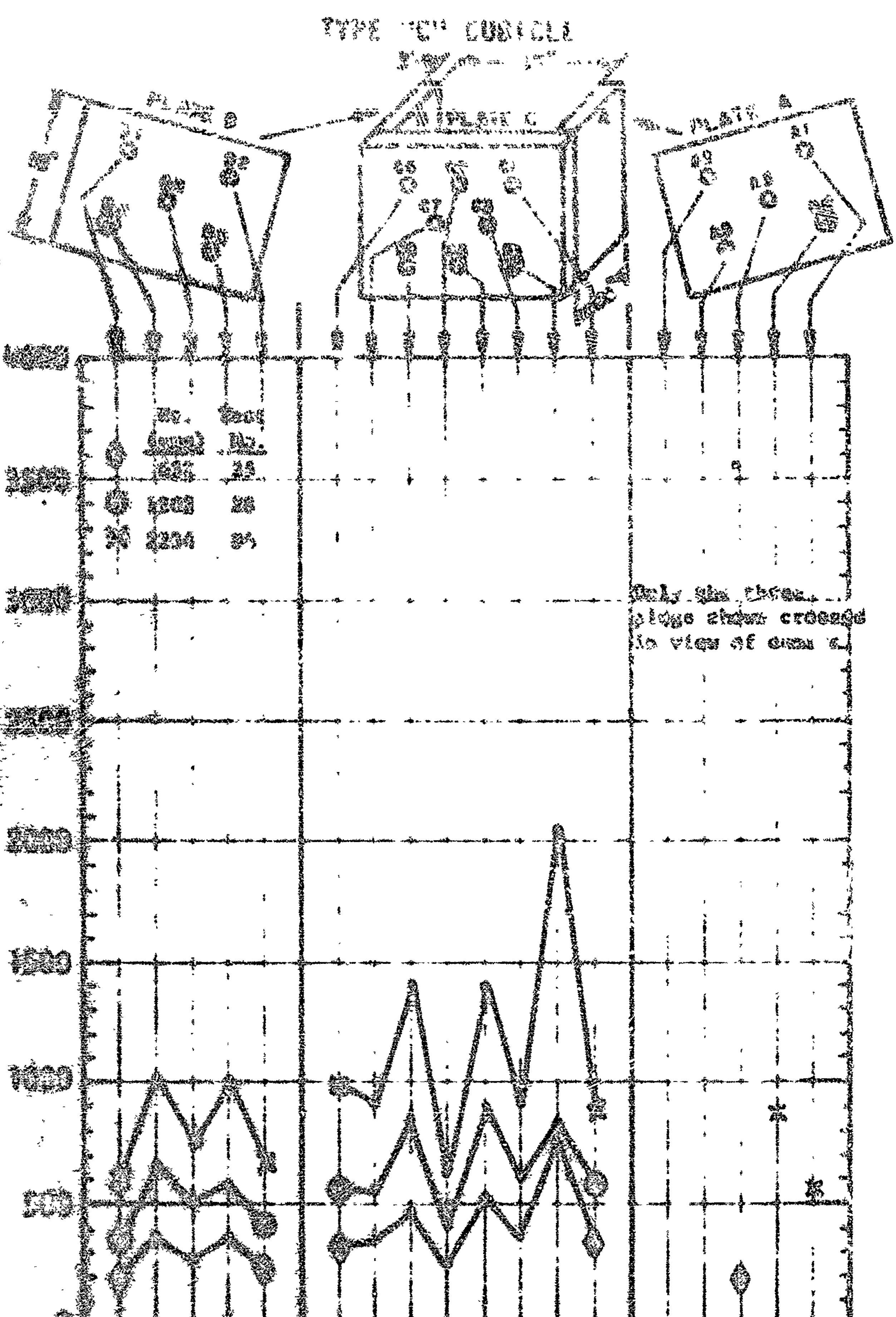


Figure 13
Impulse values at discrete points on the 3 walls from centrally initiated exploding pentolite spheres placed at the interse... of the [illegible] of the shaded plugs.

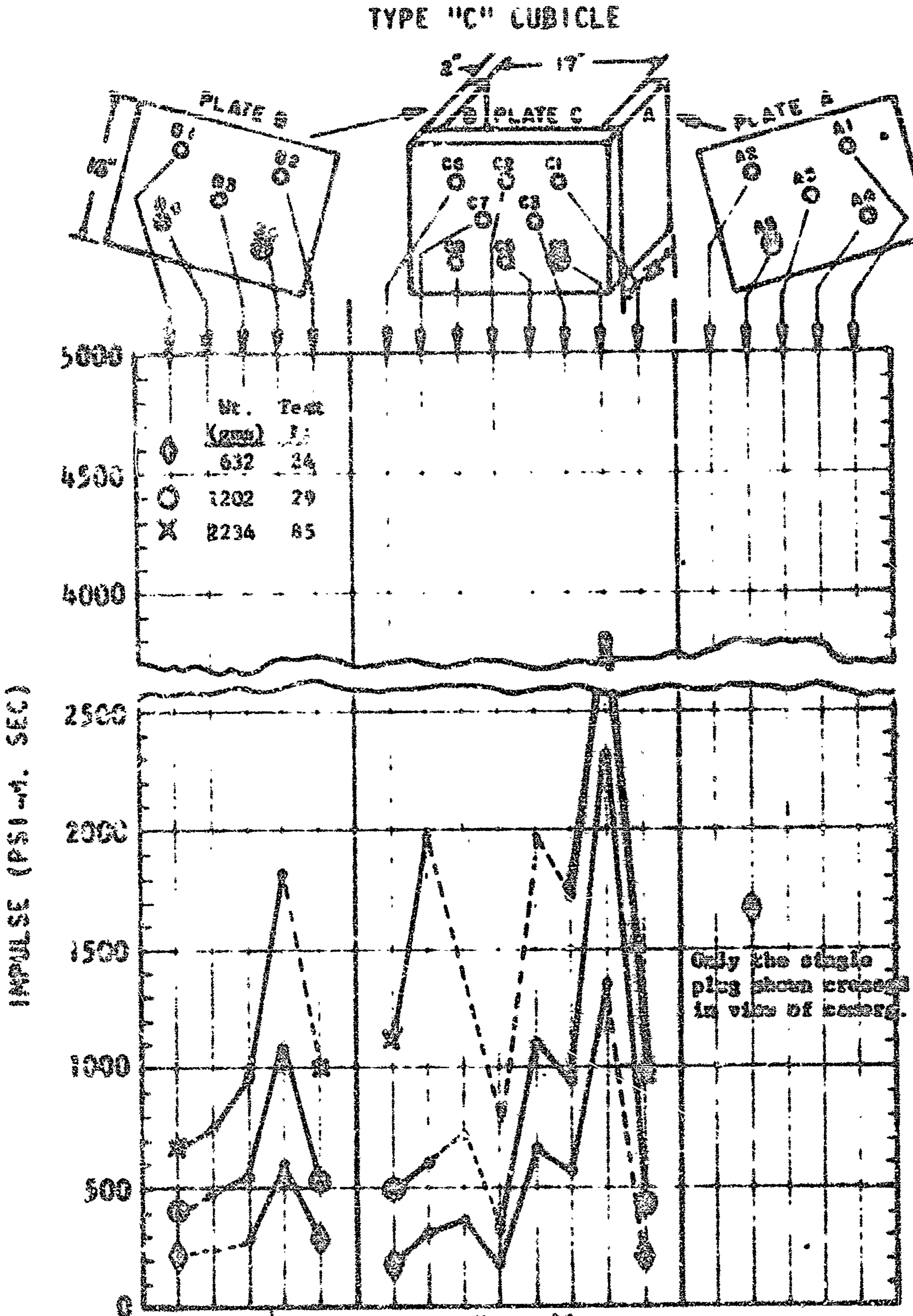


Figure 16

Impulse values at discrete points on the 3 walls from centrally initiated exploding pentolite spheres placed at the intersection of the normals of the shaded plugs.

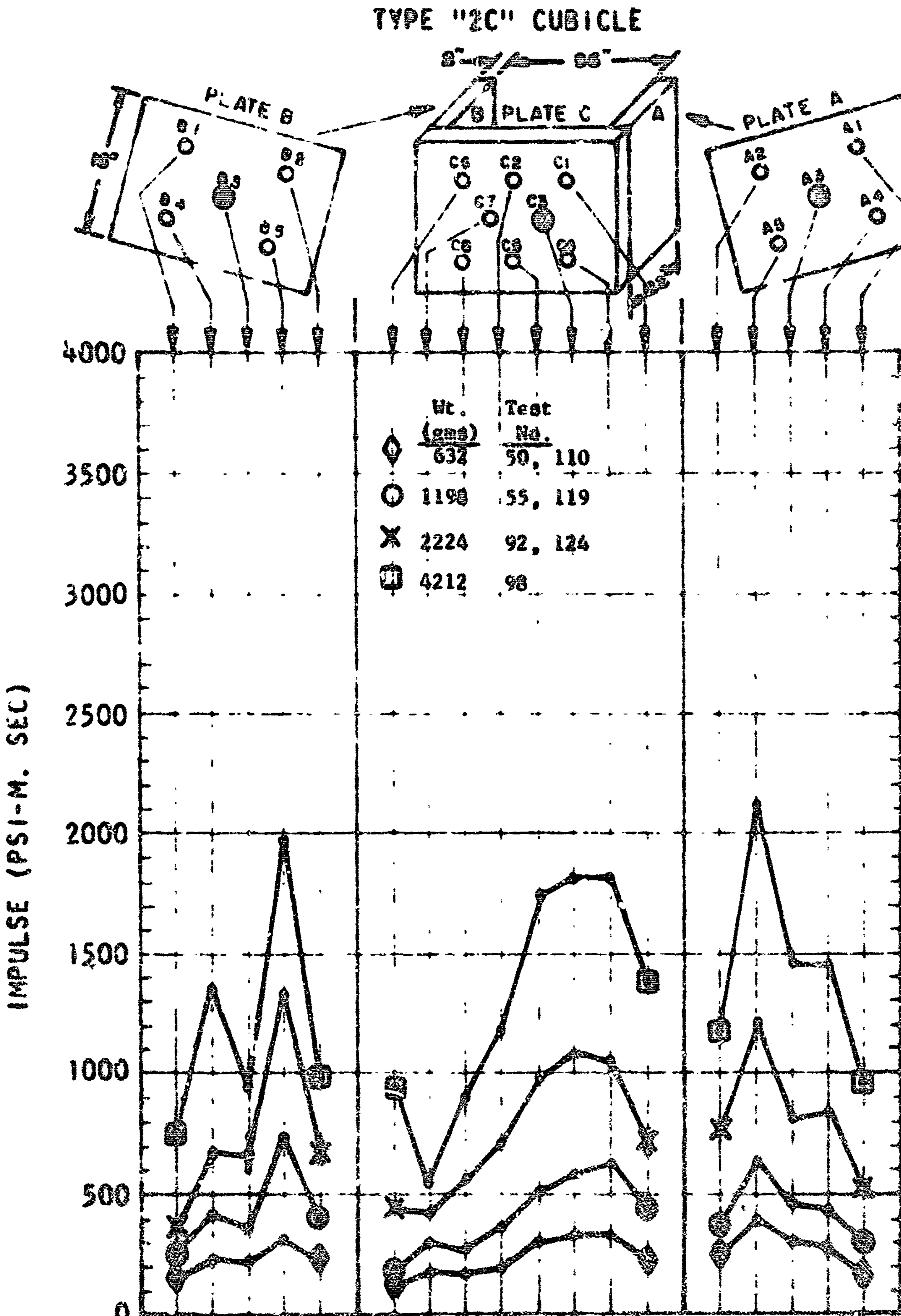
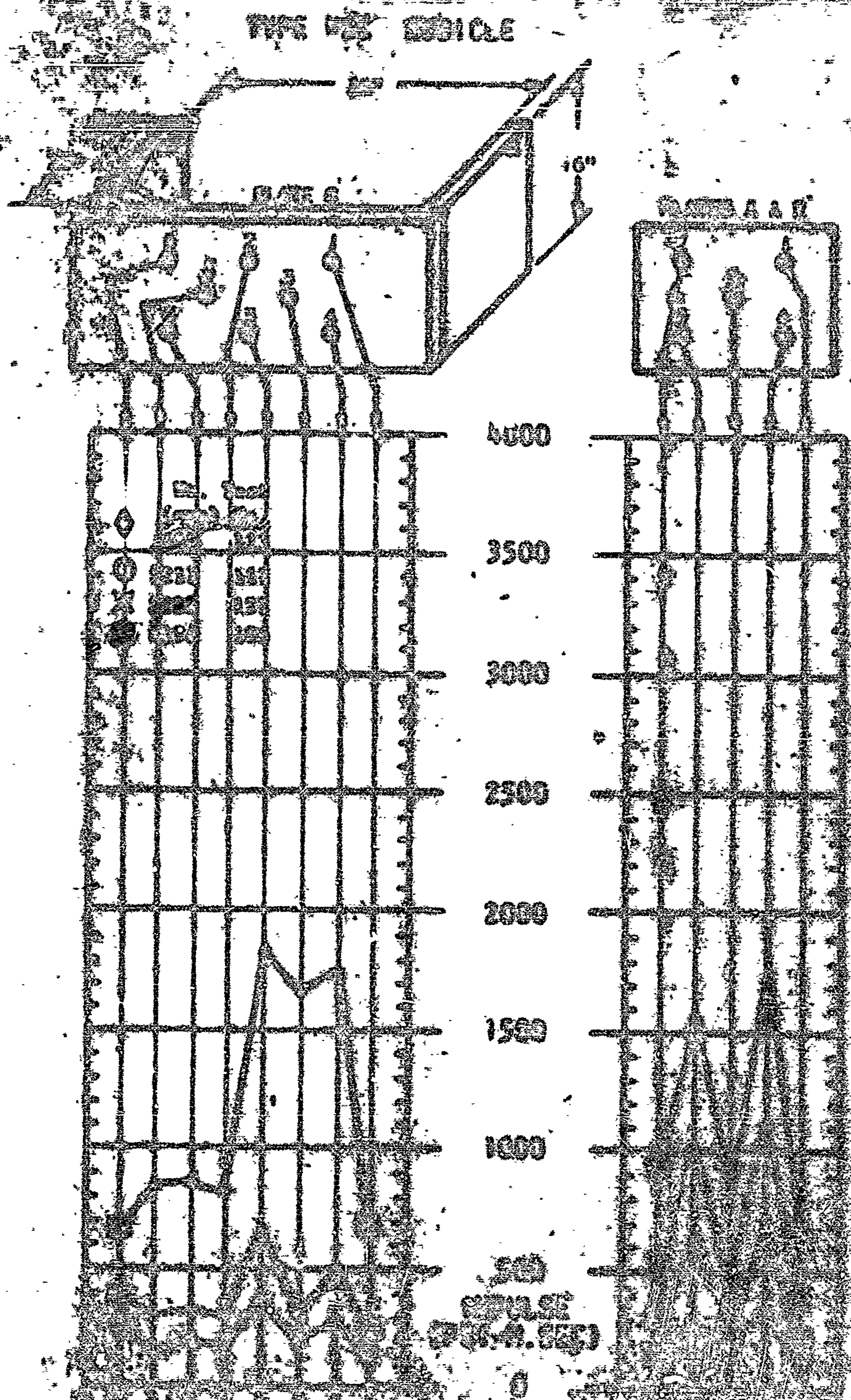


Figure 17
Impulse values at discrete points on the 3 walls from centrally initiated exploding pentolite spheres placed at the intersection of the normals of the shaded plugs.

TZ 6230



4000
3500
3000
2500
2000
1500
1000
0

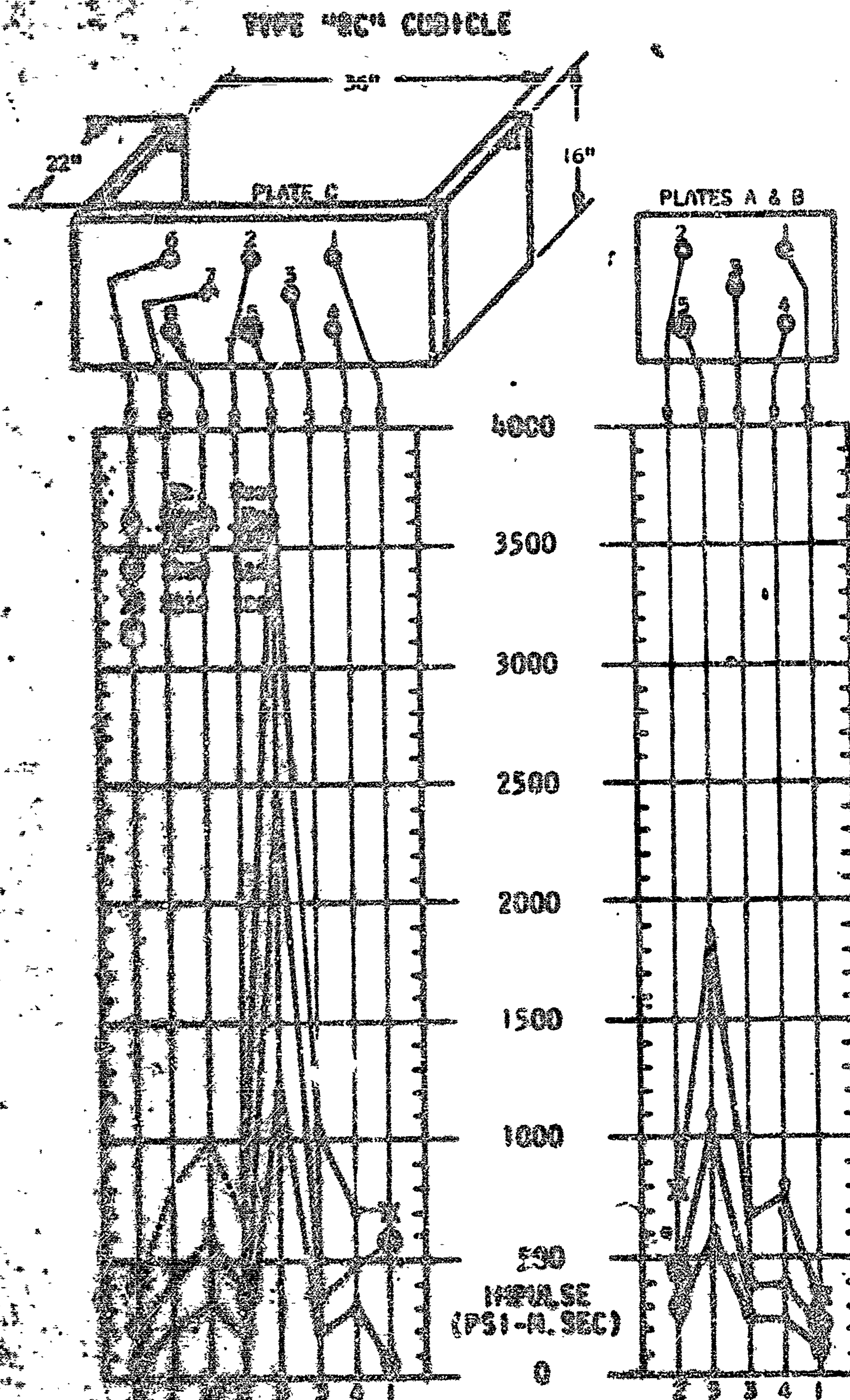
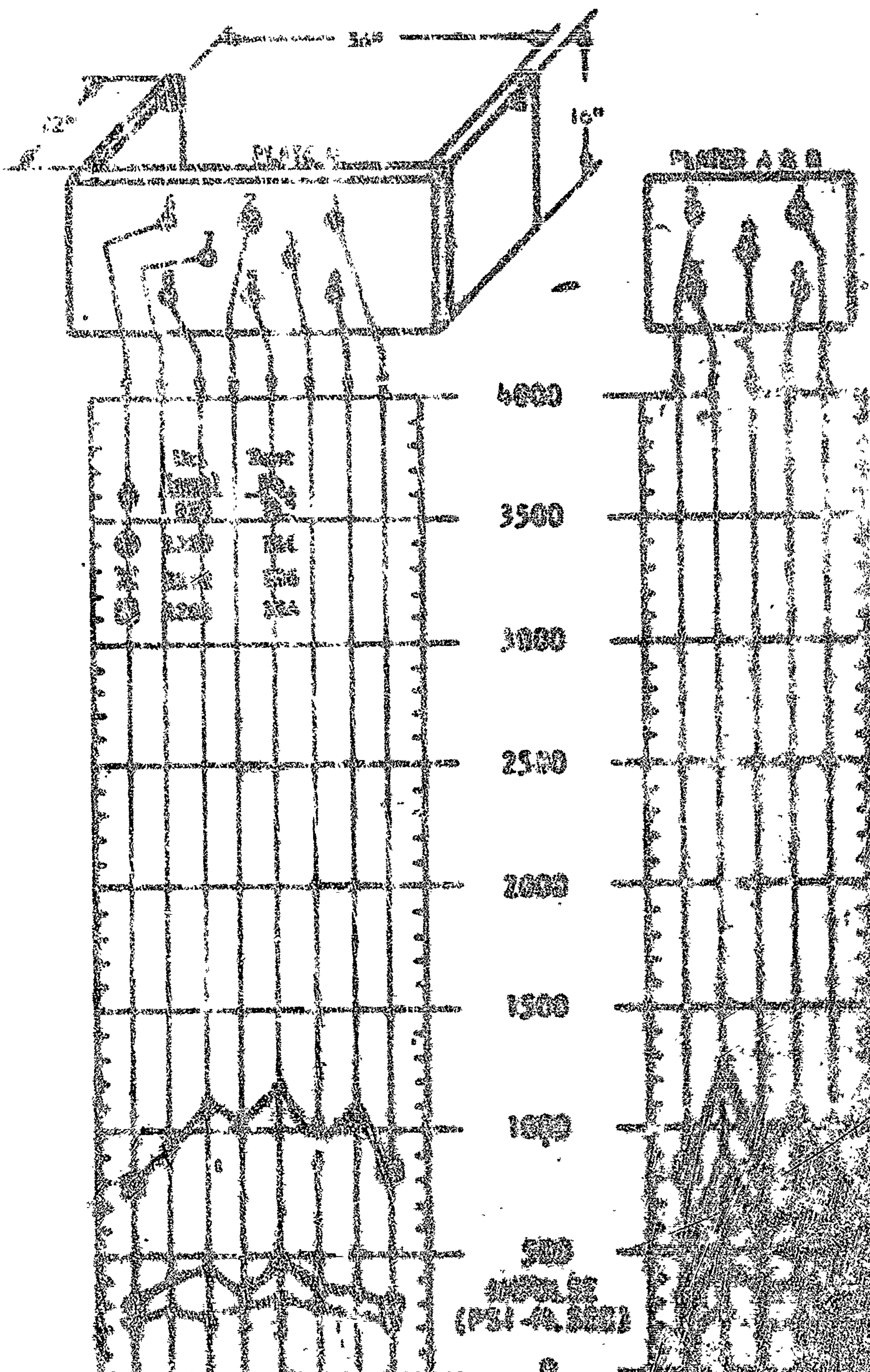
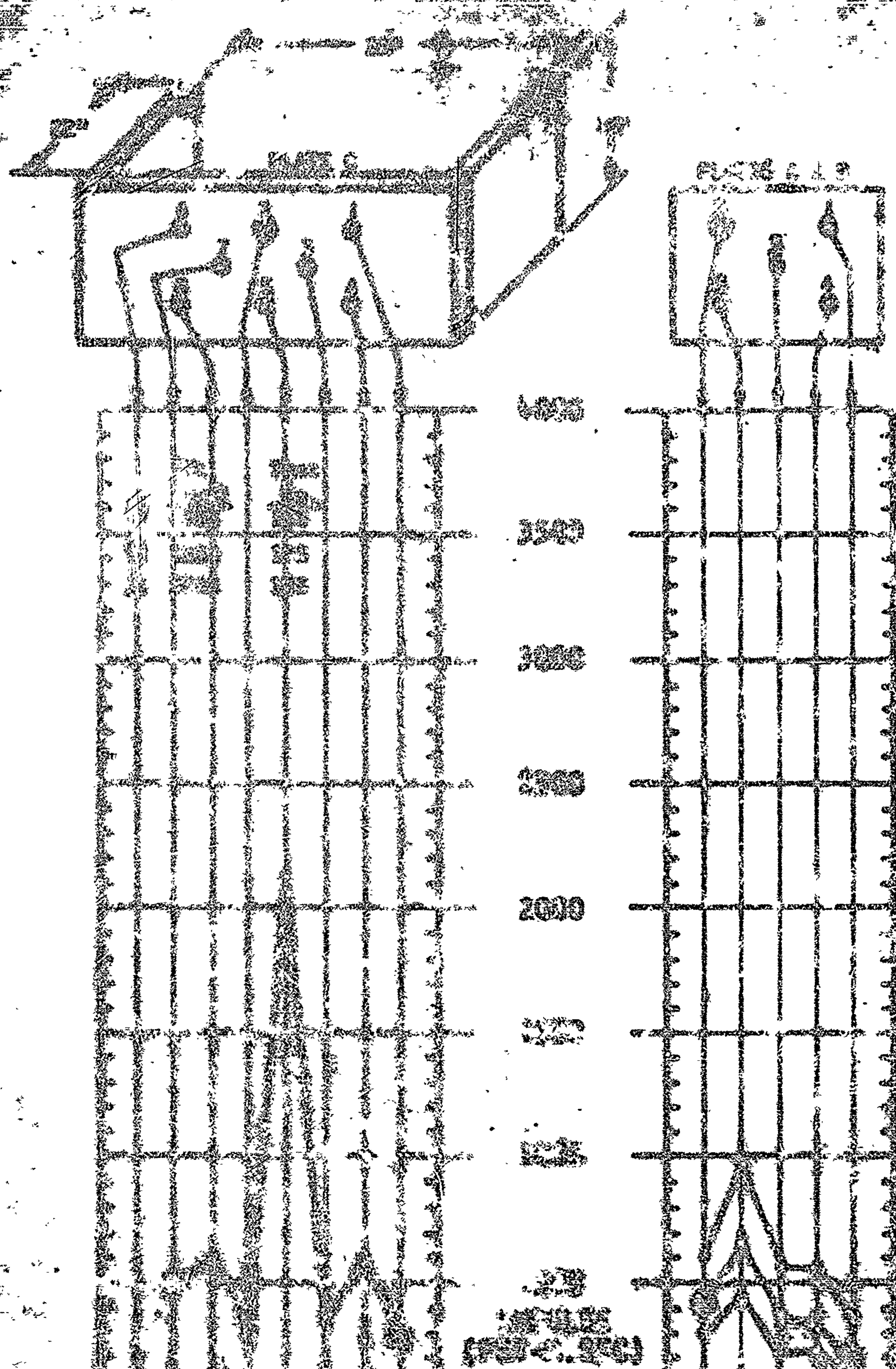


Figure [illegible]
[illegible] plates on the 3 walls from centrally [illegible] pentolite spheres placed at the [illegible] plugs.

TYPE "2C" CUBICLE




2000

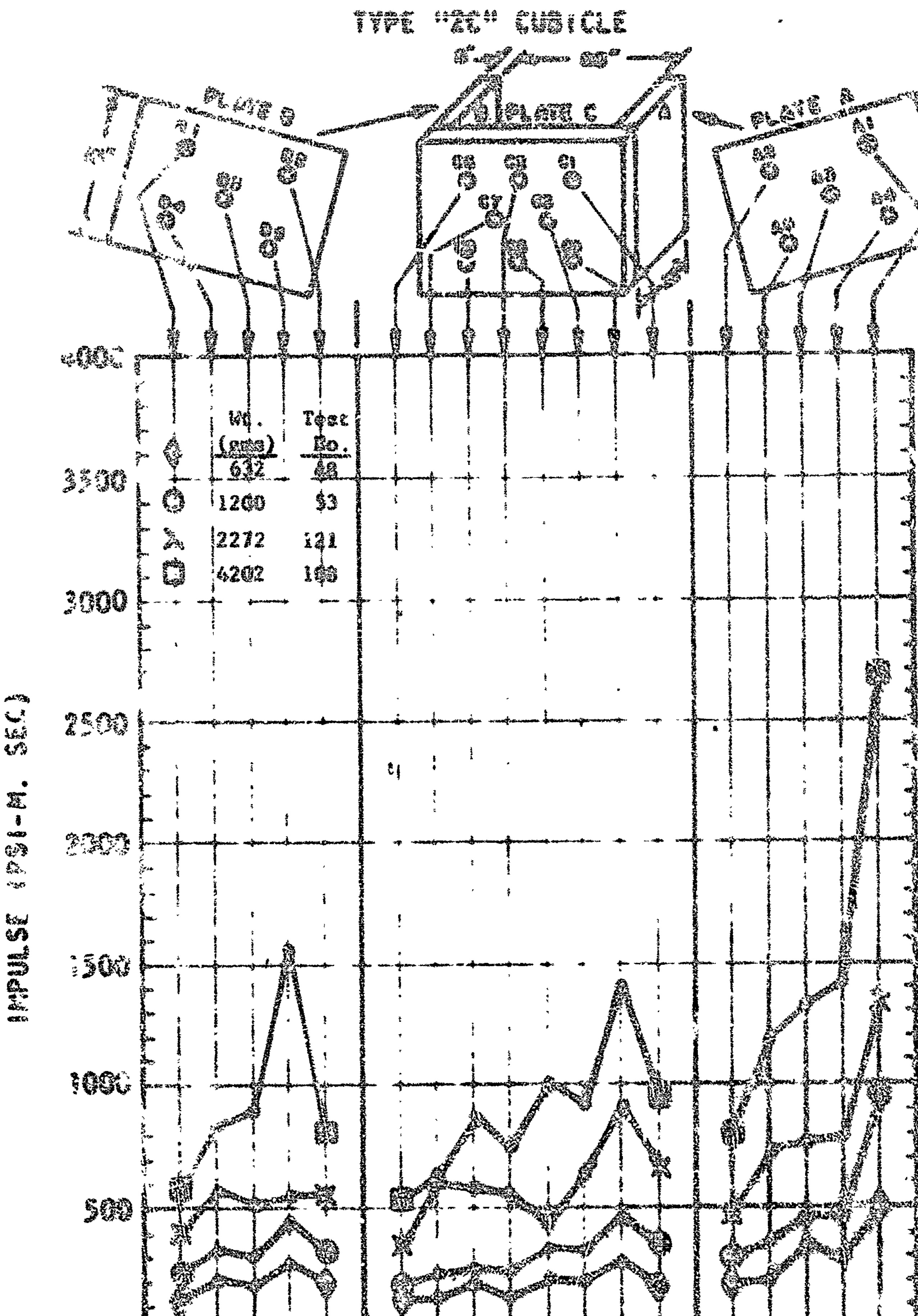


Figure 22
Impulse values at discrete points on the 3 walls from centrally initiated exploding pentolite spheres placed at the intersection of the normals of the shaded plugs.

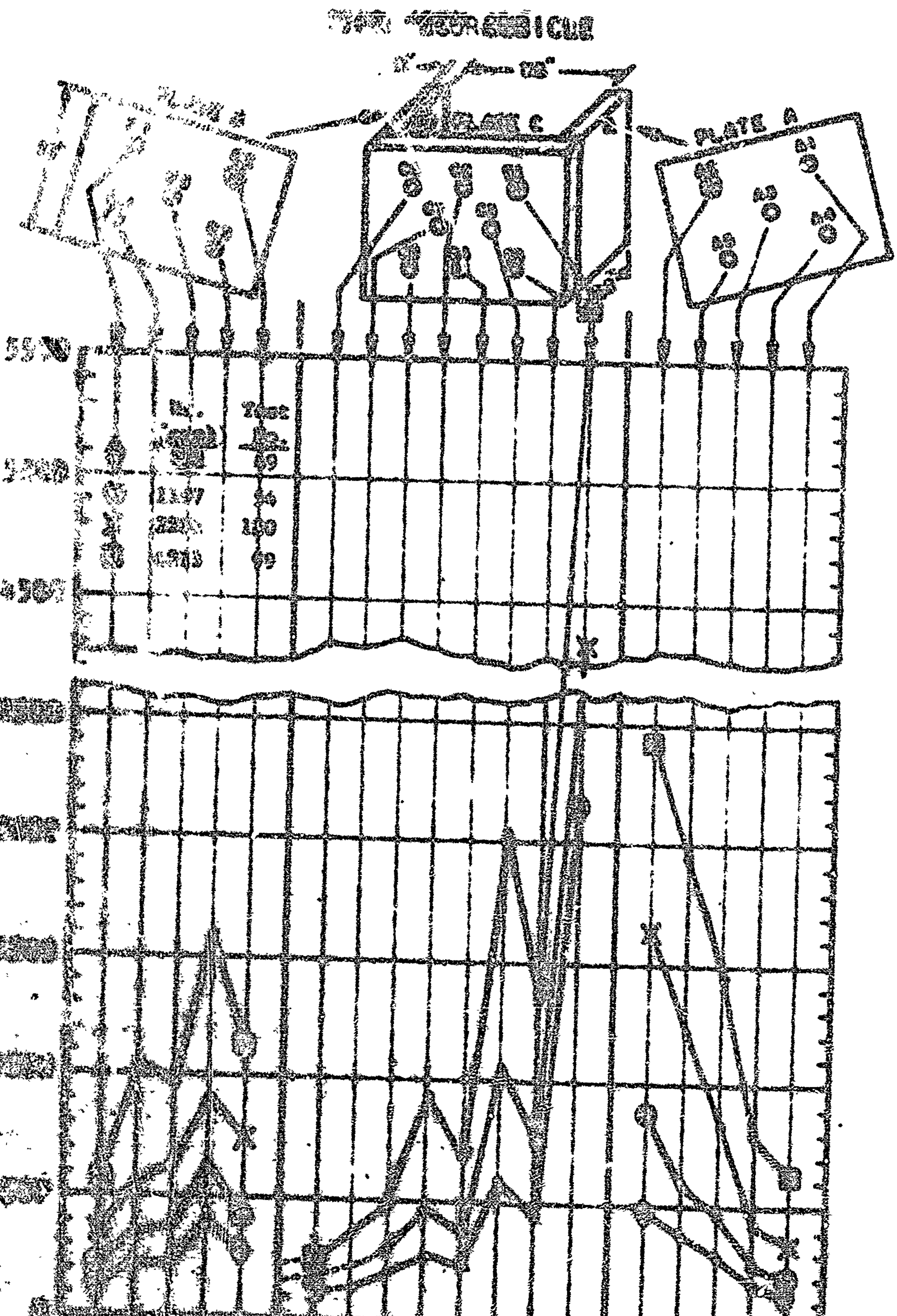


Figure 23

[illegible] at discrete points on the 3 walls from centrally [illegible] spheres placed at the intersection of [illegible] plates.

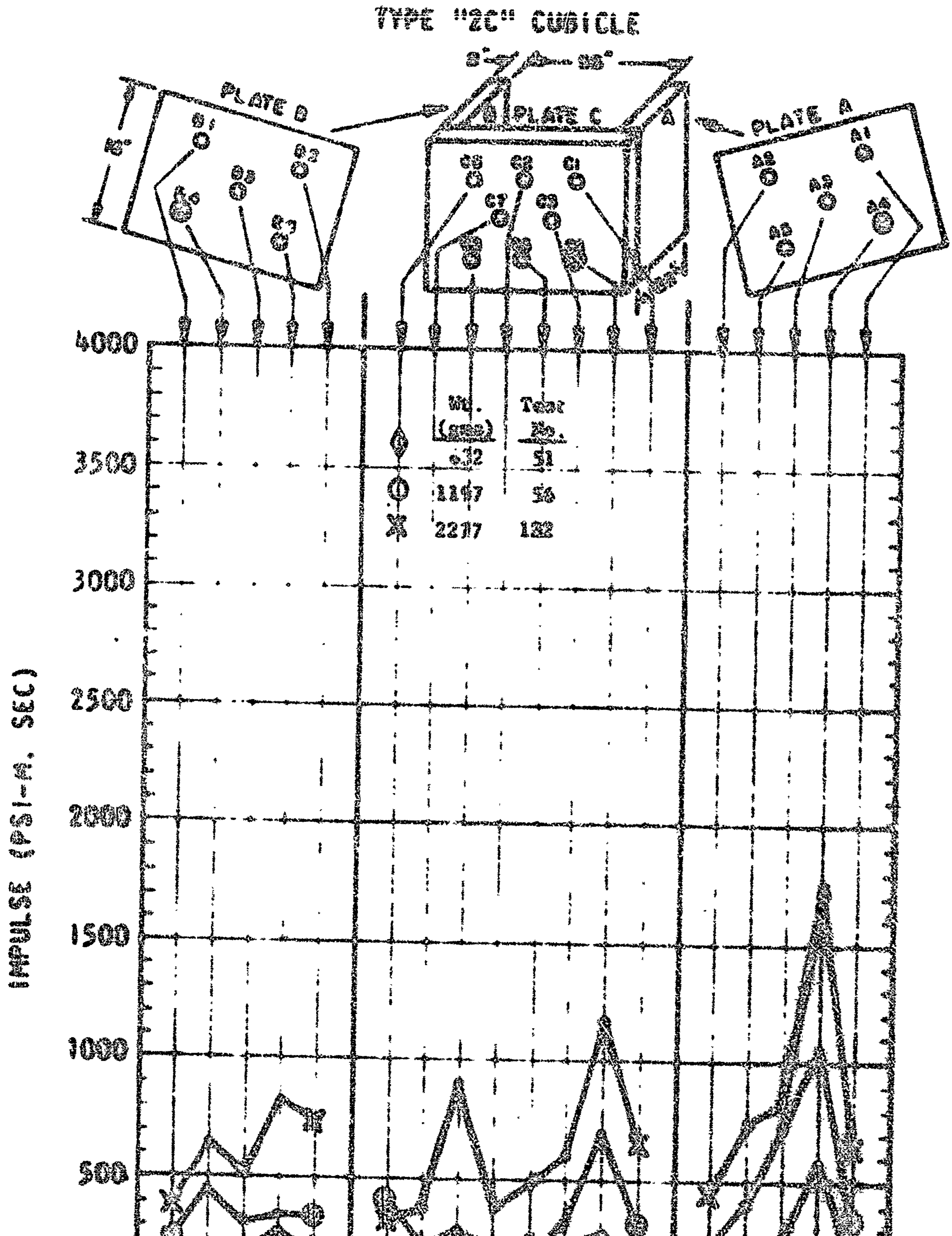


Figure 26
Impulse values at discrete points on the 3 walls from centrally initiated exploding pentolite spheres placed at the intersection of the normals of the shaded plugs.

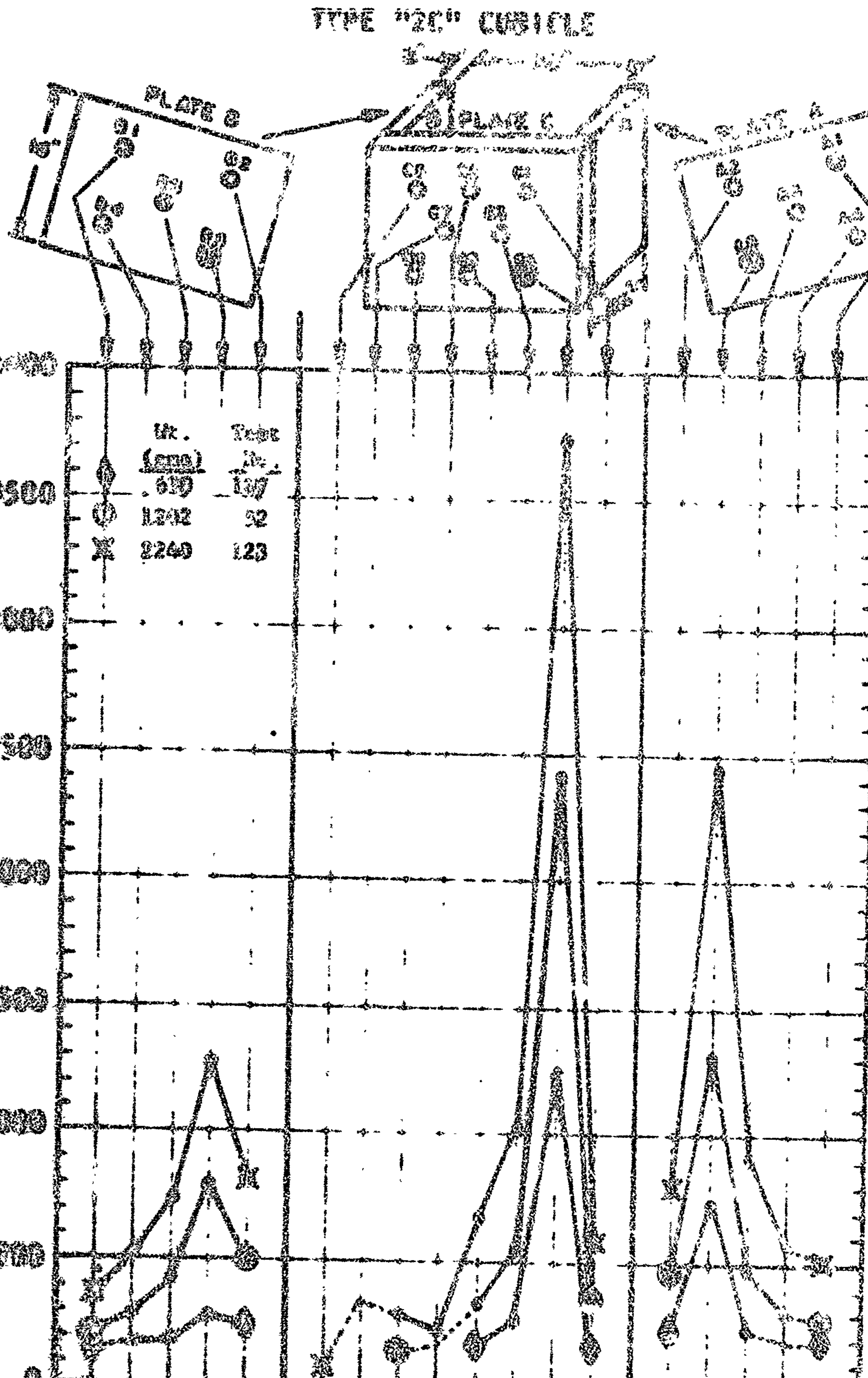


Figure 29

Impulse values at discrete points on the 3 walls from centrally initiated exploding pentolite spheres placed at the intersection of the normals of the shaded plugs.